The Hyper-Kamiokande Experiment: design, status of construction and physics goals

31^{st} International Symposium on Lepton Photon Interactions at High Energies
Melbourne, Australia

19^{th} July 2023

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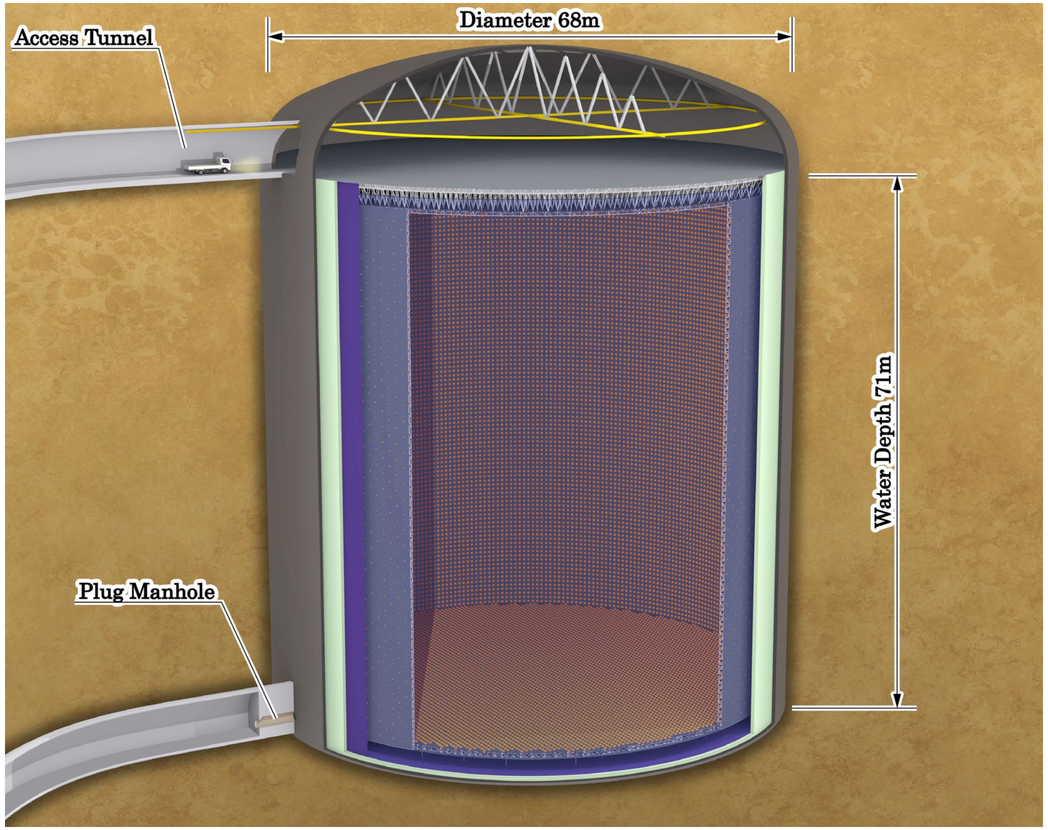
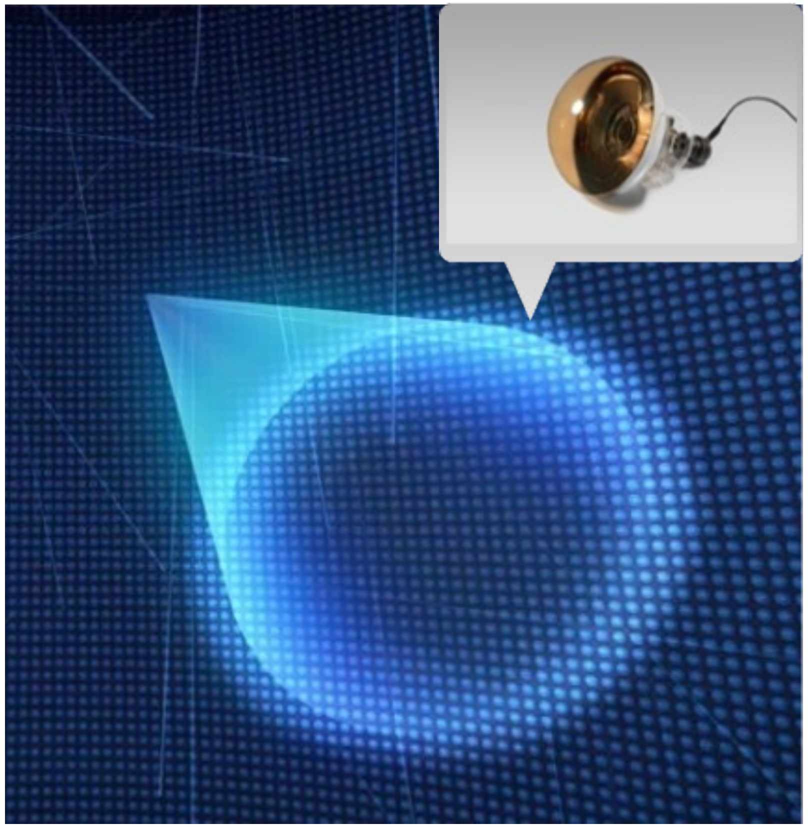
Science and Technology Facilities Council

LEVERHULME TRUST

Hyper-Kamiokande Detector

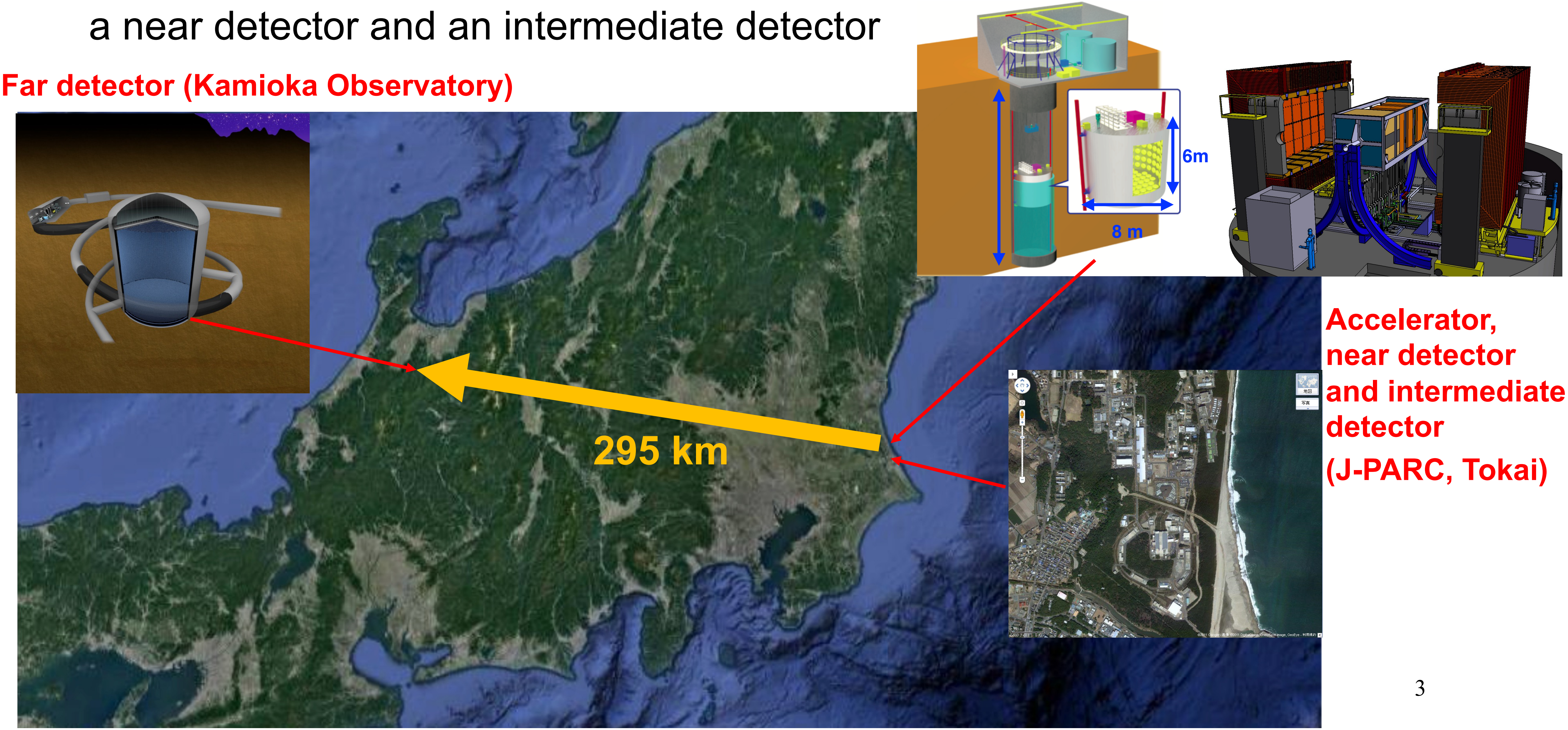
- The Hyper-Kamiokande detector is the next generation water Cherenkov detector in Kamioka, Japan, with an accelerator and near detector complex at J-PARC in Tokai
- Size: 258 kton, with fiducial mass ~8 times larger than Super-K,
- Baseline: 20,000 50-cm photomultiplier tubes (PMT), ~2,000 multi-PMT modules and 7,200 outer detector 8-cm PMTs with wavelength shifting (WLS) panels





Hyper-Kamiokande Project

- The Hyper-Kamiokande project includes a far detector, a neutrino beam, a near detector and an intermediate detector

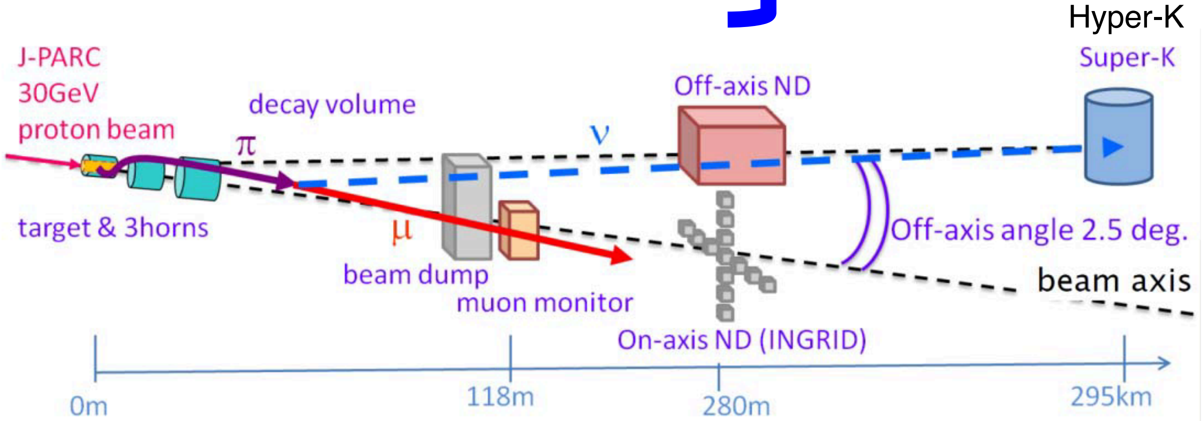


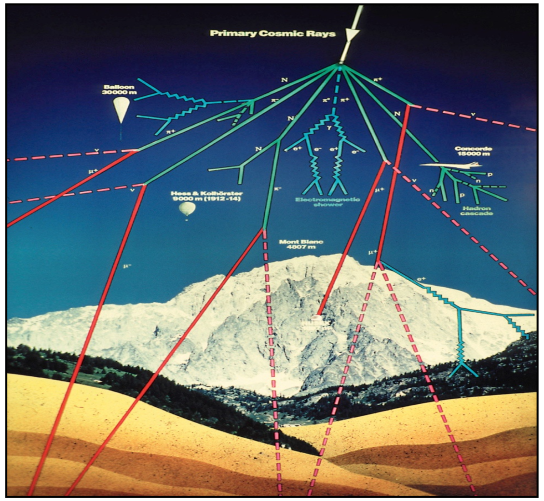
Science goals Hyper-Kamiokande

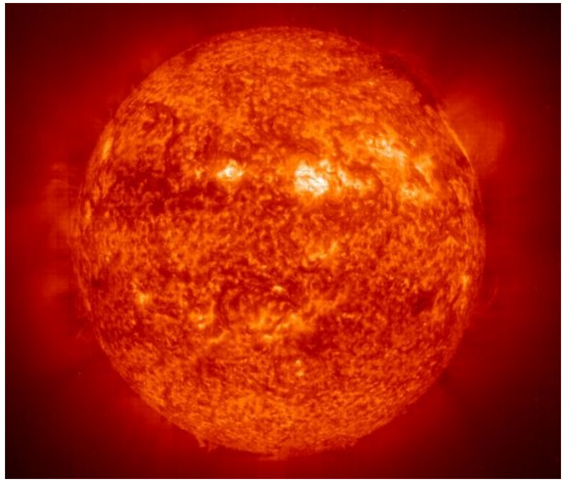
Hyper-Kamiokande

- Hyper-Kamiokande is both a microscope and a telescope
  - Accelerator neutrinos
  - Atmospheric neutrinos
  - Solar neutrinos

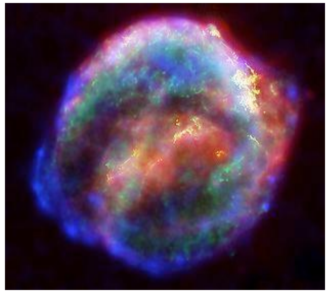
Neutrino oscillation, matter effects, mass ordering, CP violation, sterile neutrinos, non-standard interactions



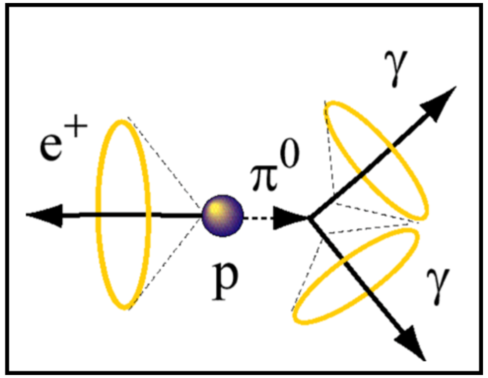




  - Neutrino astrophysics: **Supernova burst, pre-supernova neutrinos and supernova relic neutrinos**



Beyond Standard Model, Grand Unified Theories:
$p \rightarrow e^{+}\pi^{0}$ and $p \rightarrow \bar{\nu}K^{+}$



  - Proton decay:

Neutrino oscillations

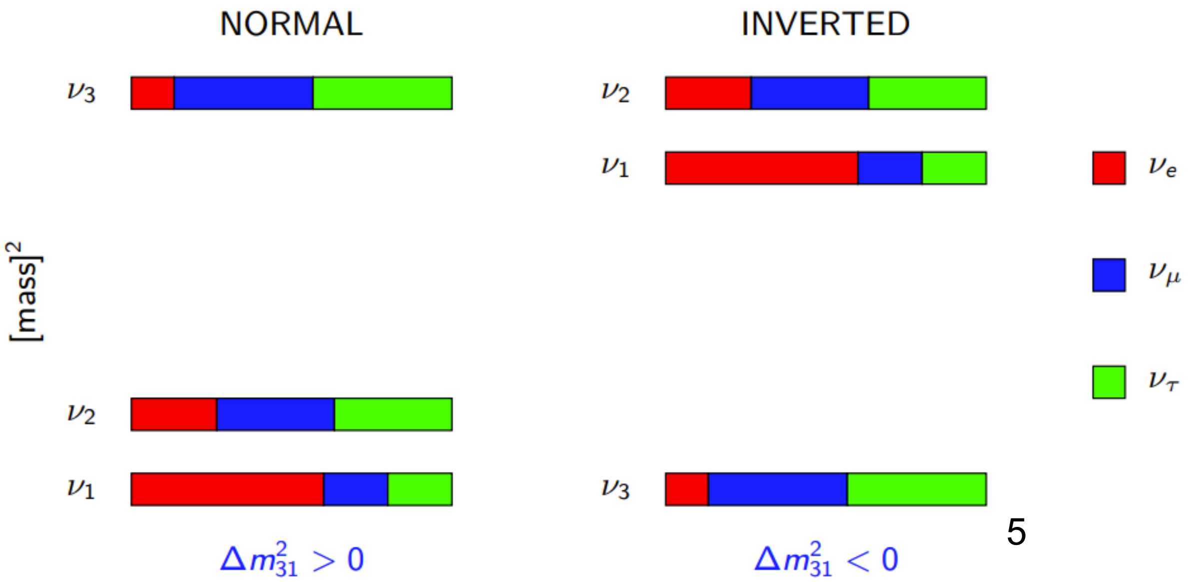
Hyper-Kamiokande

- Mixing between flavour states and mass states of neutrinos

$$c_{ij} = \cos\theta_{ij},\ s_{ij} = \sin\theta_{ij}$$

$$U_{PMNS} = \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar, reactor neutrinos}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric, accelerator neutrinos}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor, accelerator neutrinos}}$$

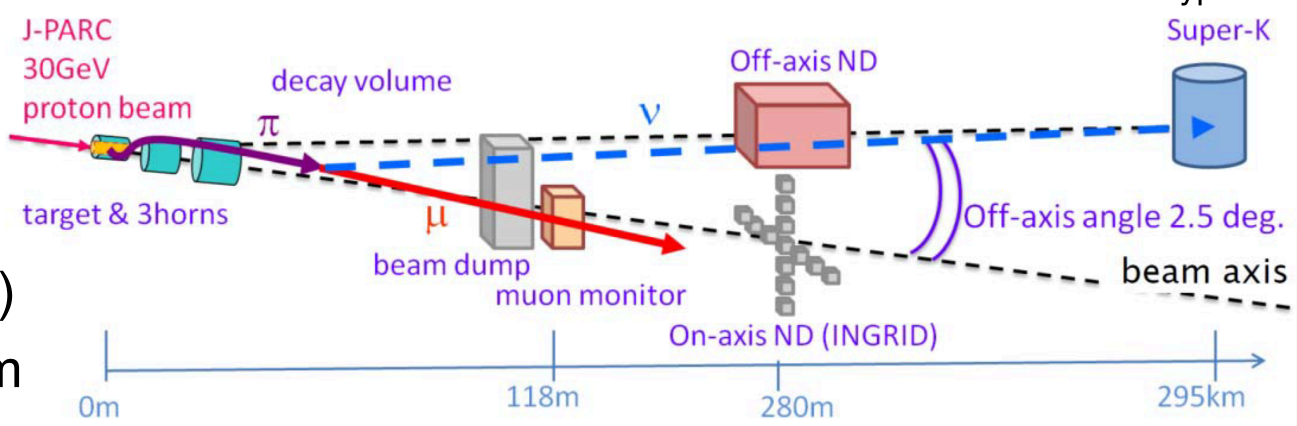
- Remaining questions:
  - CP violation phase: δ_{CP} (matter-antimatter)
  - Mass ordering: sign of Δm^2_{13}
  - Is θ_{23} maximal?



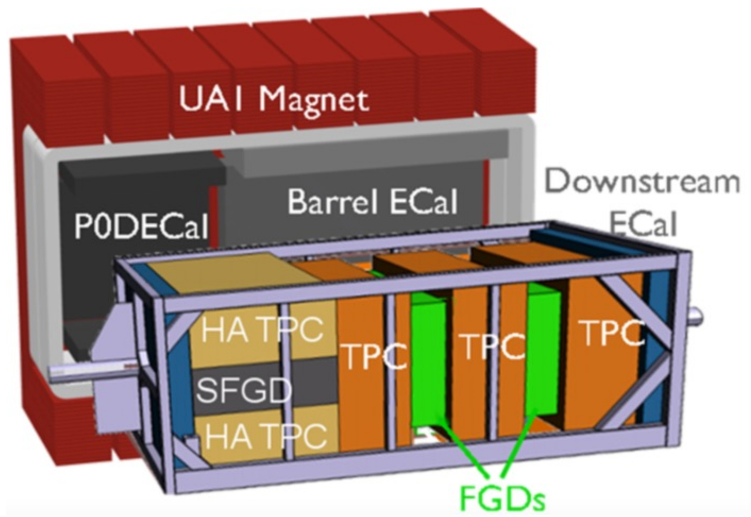
Neutrino oscillations in Hyper-K with neutrino beam

Hyper-Kamiokande

- Off-axis at 2.5° neutrino beam to achieve maximum neutrino flux at oscillation maximum of 0.6 GeV, beam upgrade from 515 kW to 1.3 MW
  - Power supply upgrade: 250 kA → 320 kA;
  - Cycle: 2.48 s → 1.32 s → 1.16 s/cycle
- Upgrade of ND280: October 2023
  - New Super-Fine Grained Detector (SFGD)
  - High-Angle TPC and Time-of-Flight system

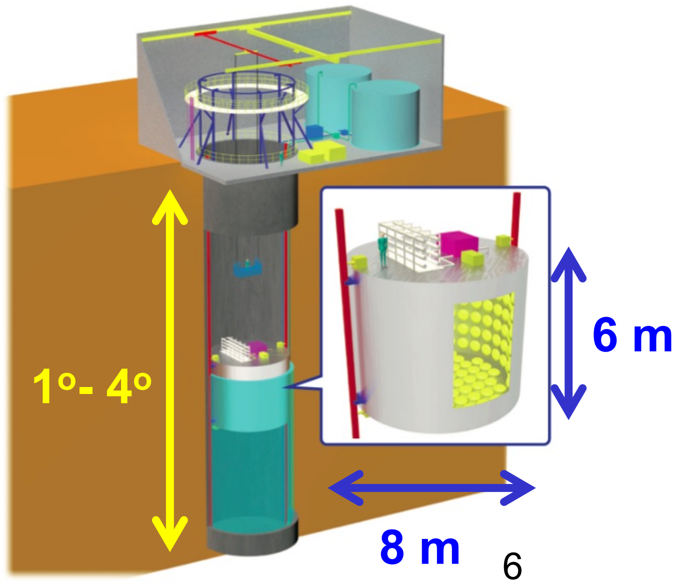


- New Intermediate Water Cherenkov Detector (IWCD):



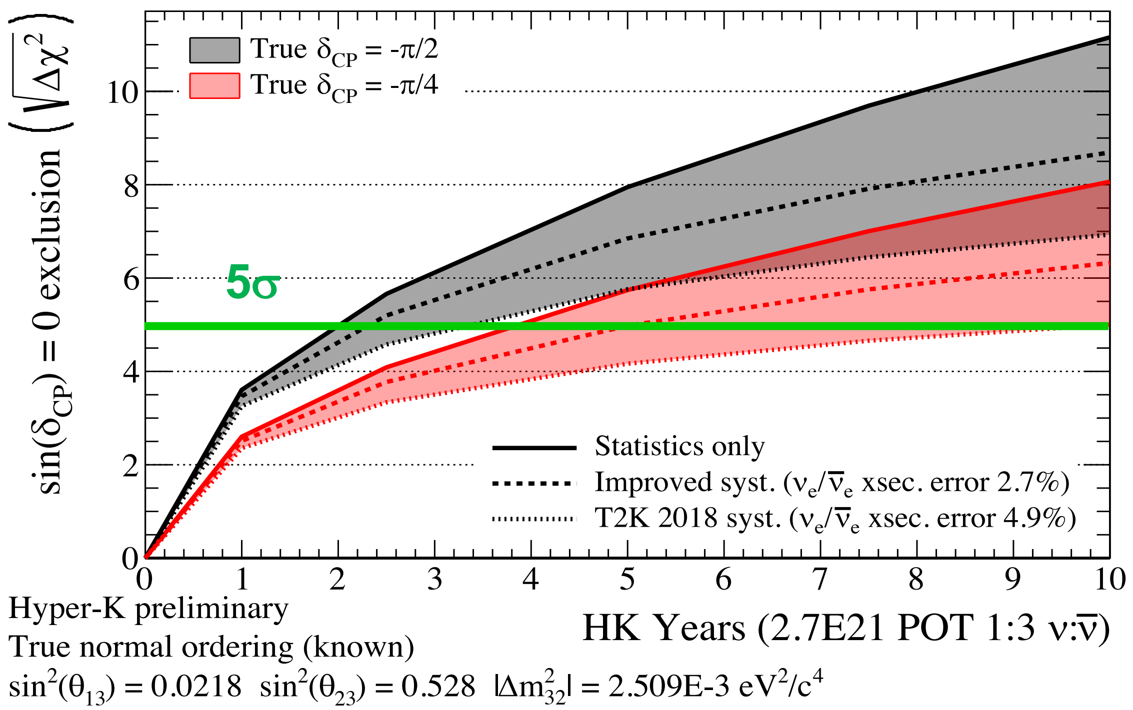
Uses PRISM approach: change off-axis angle 1° – 4° to change mean neutrino energy and constrain:

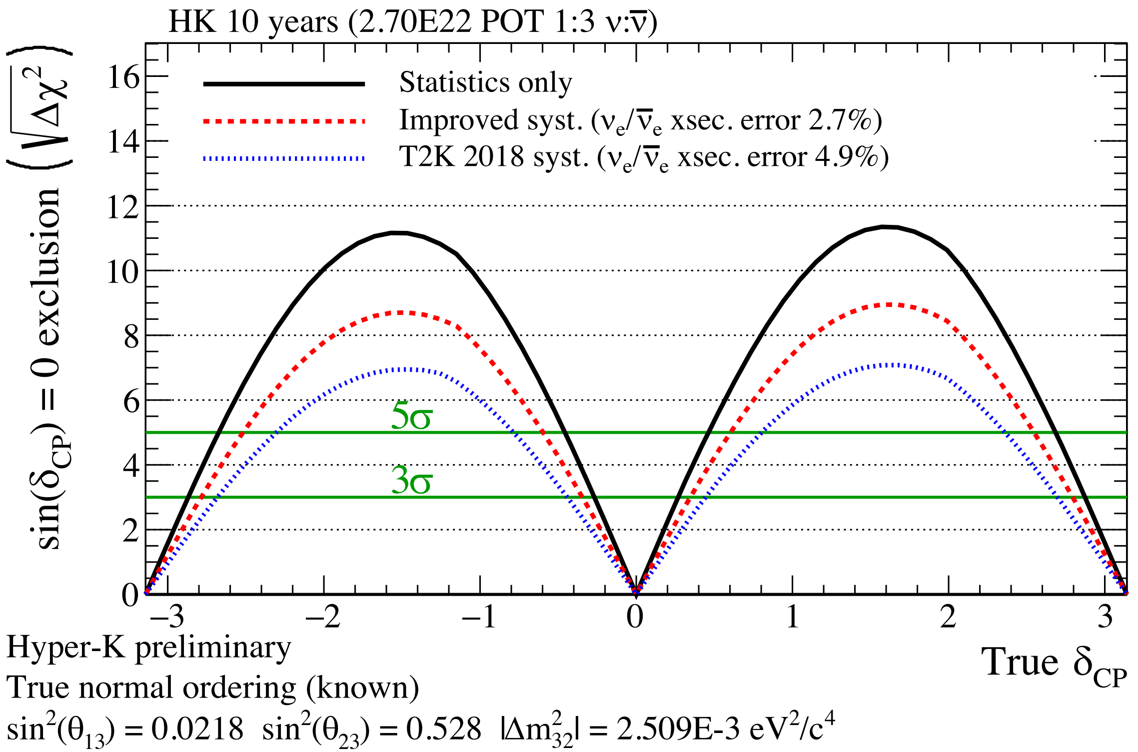
$$\frac{\sigma(\nu_e)/\sigma(\nu_\mu)}{\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)}$$



Neutrino oscillation sensitivity in Hyper-K

- Sensitivity CP violation with 1:3 $\nu:\bar{\nu}$ beam

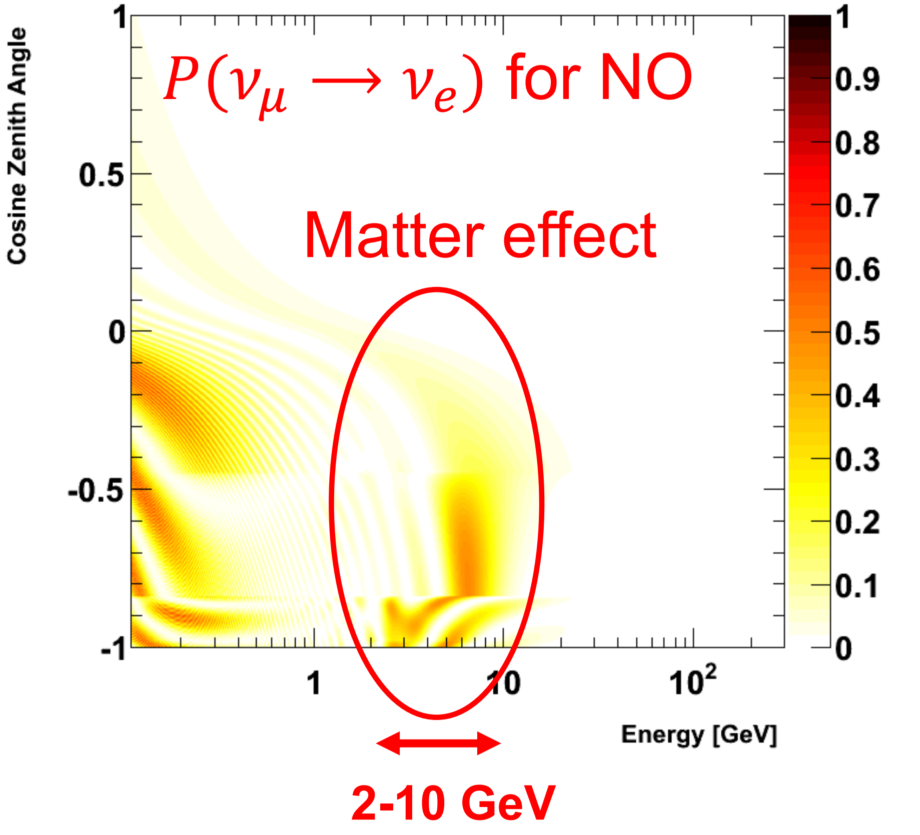


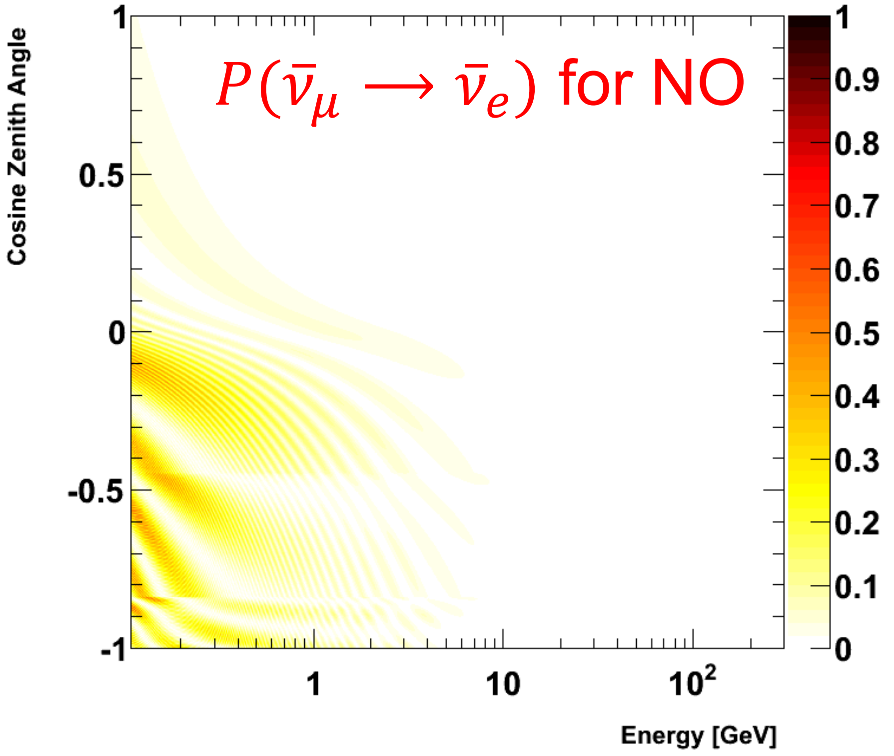


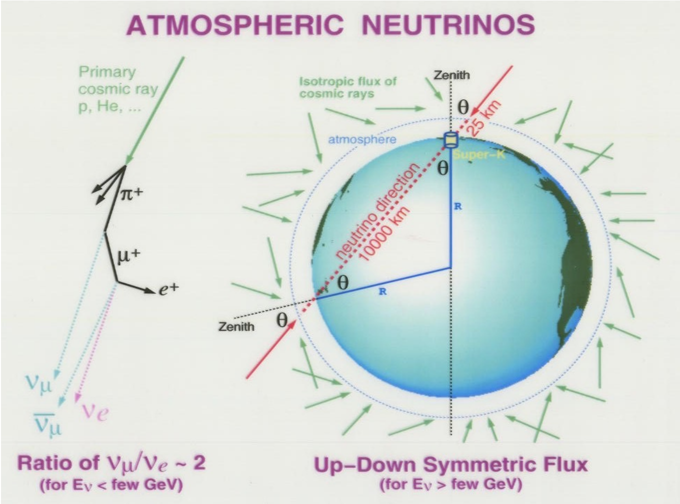
- With optimistic systematics and known mass ordering (MO): 2-3 years for 5σ sensitivity to exclude CP conservation for true $\delta_{CP} = -\pi/2$.
- After 10 year operation, 60% of δ_{CP} values excluded at > 5σ.

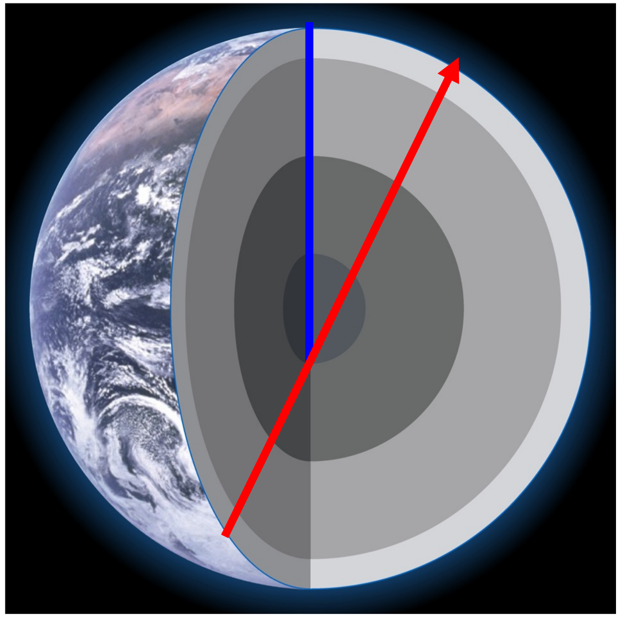
Atmospheric neutrino oscillation

- Atmospheric neutrinos measure direction of cosmic rays and are sensitive to mass ordering (MO)
- Enhancement of $P(\nu_\mu \longrightarrow \nu_e)$ for NO and $P(\bar{\nu}_\mu \longrightarrow \bar{\nu}_e)$ for IO







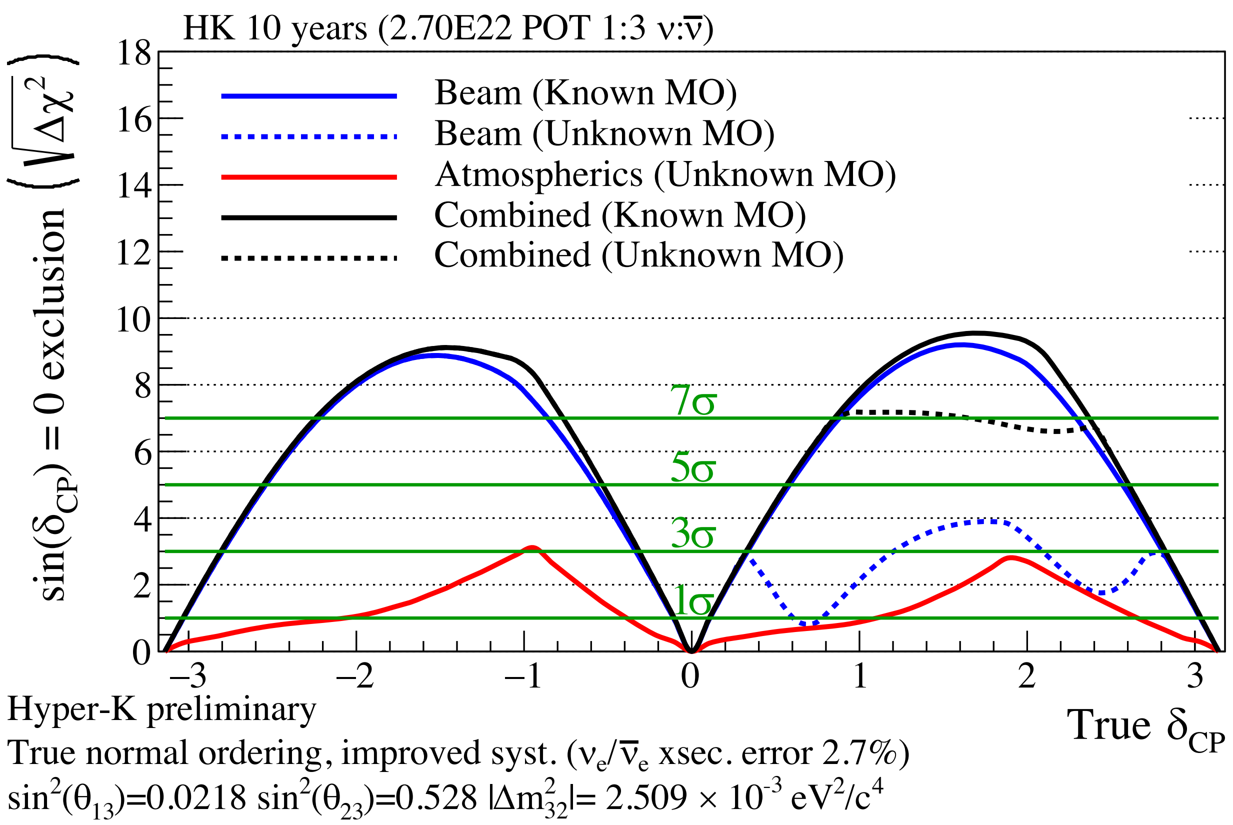


Super-K, Phys. Rev. D **97**, 072001

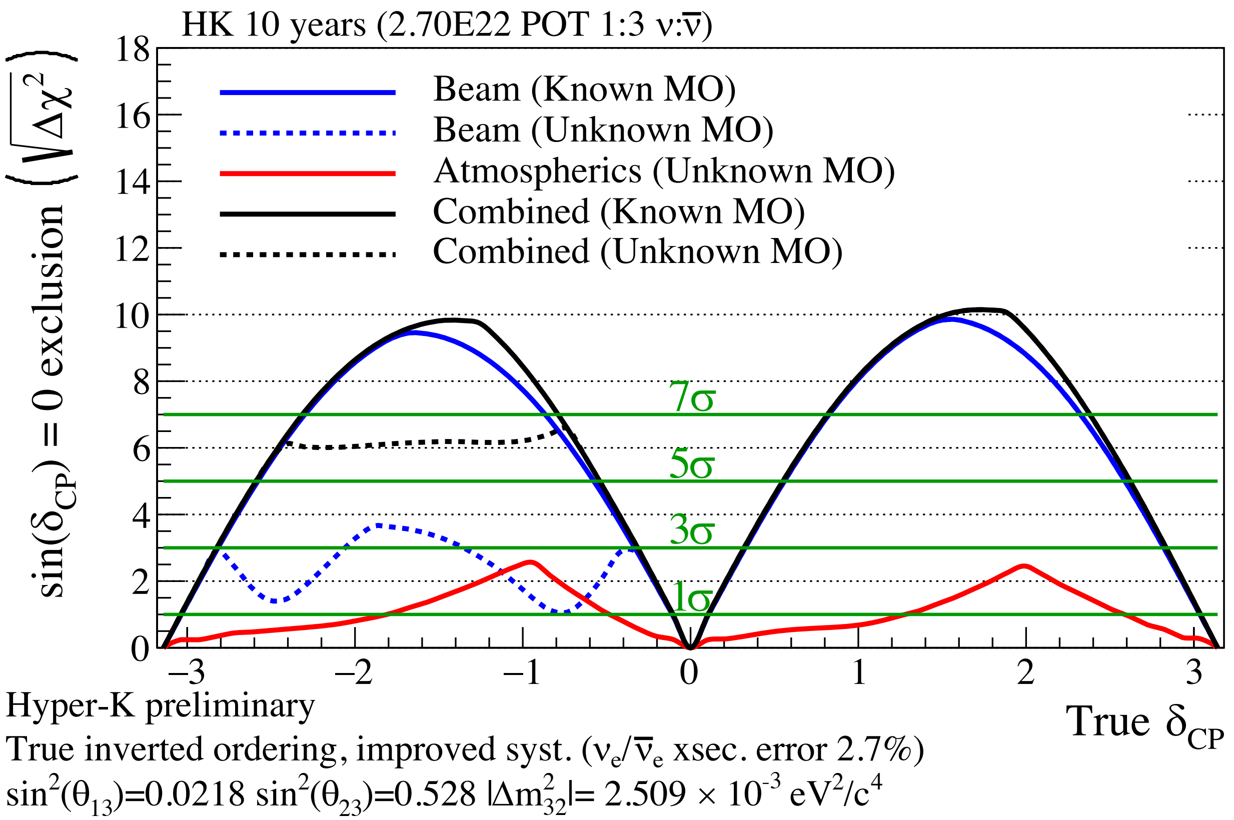
CP violation sensitivity with atmospherics

- Sensitivity CP violation with 1:3 $\nu:\bar{\nu}$ beam with atmospherics, with and without MO

Normal ordering

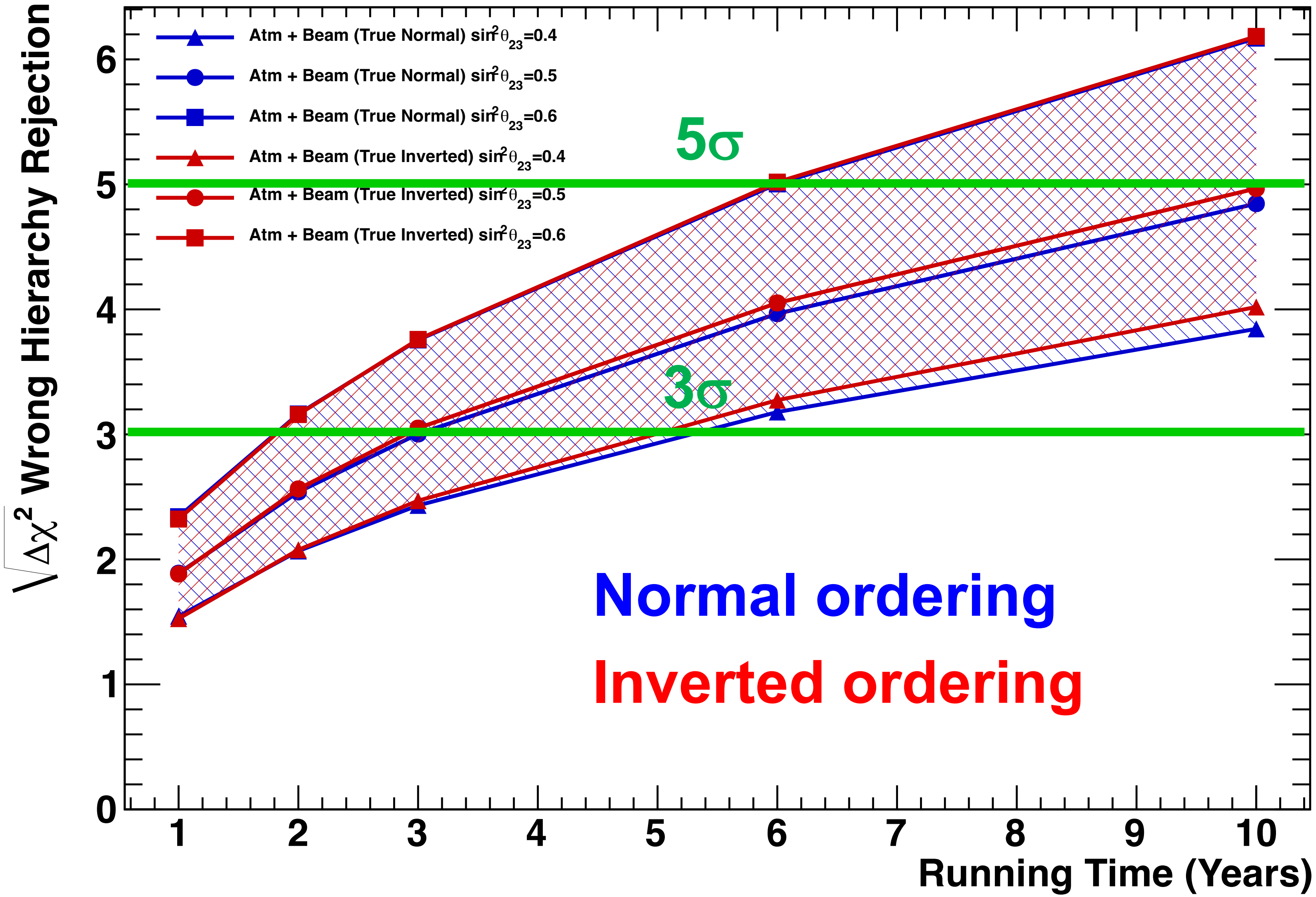


Inverted ordering



Mass ordering sensitivity with beam and atmospherics

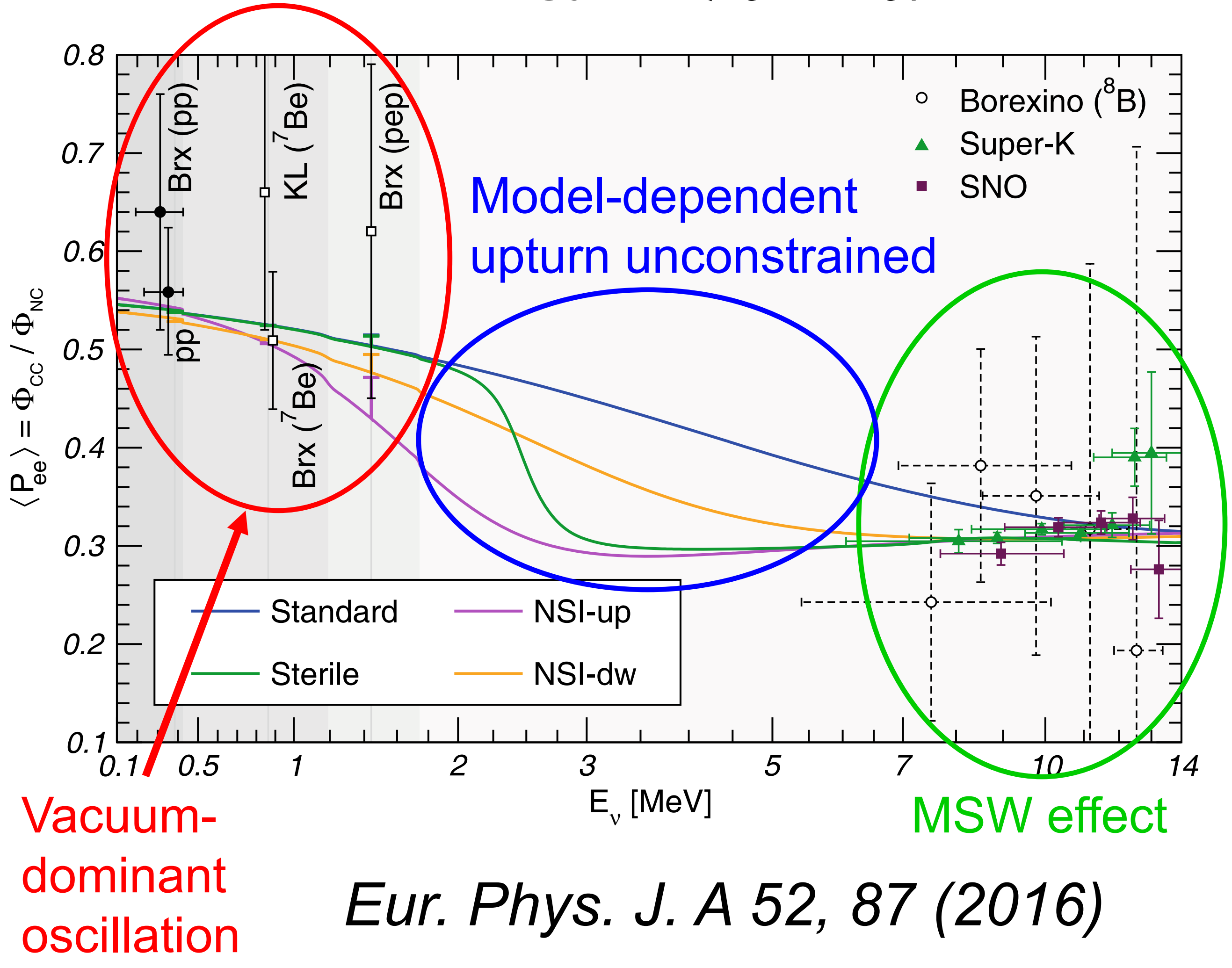
- After 10-year operation, mass ordering can be determined with 4σ - 5σ

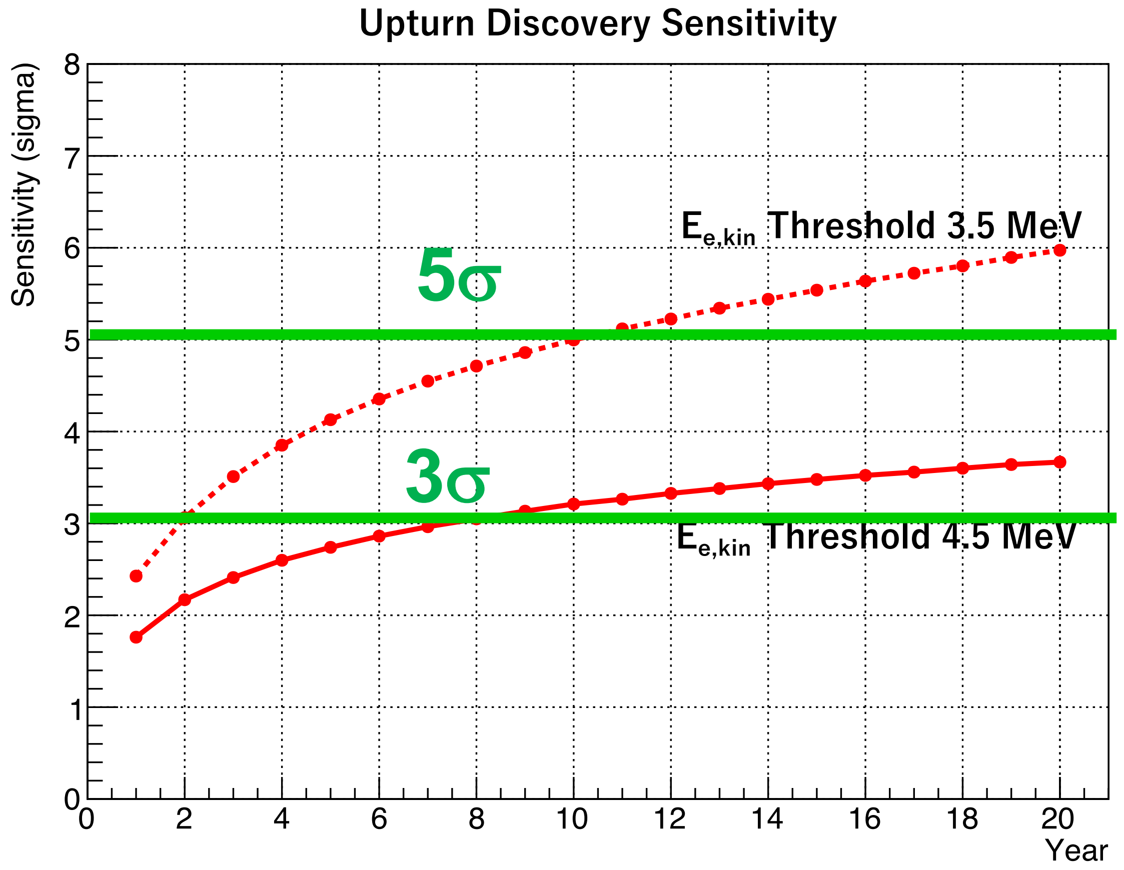


Solar neutrinos

Hyper-Kamiokande

- Solar neutrino oscillations are enhanced by matter (MSW) effects as function of energy - $P(\nu_e \rightarrow \nu_e)$ falls with energy





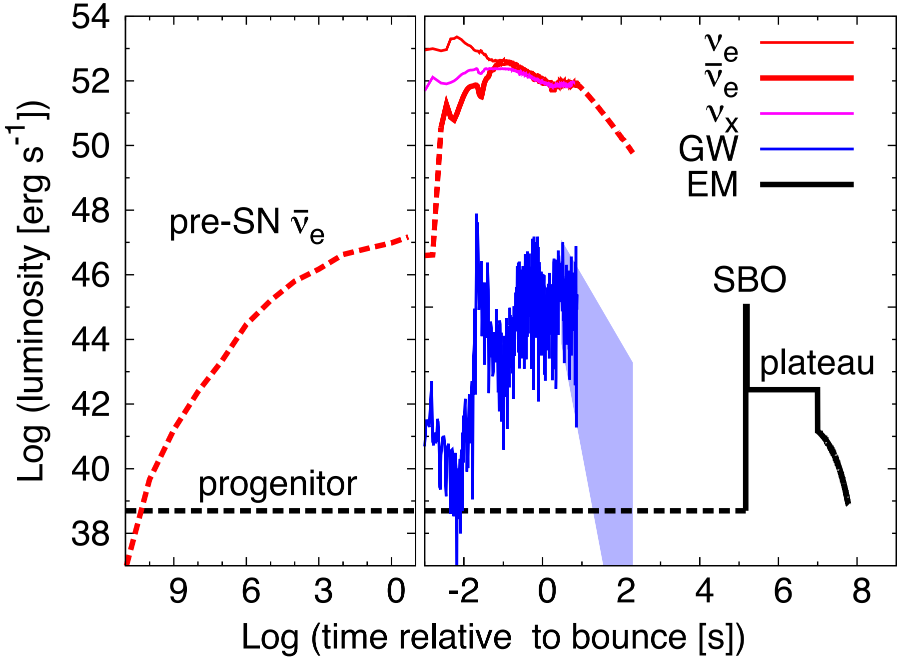
Eur. Phys. J. A 52, 87 (2016)

Supernova neutrinos in Hyper-Kamiokande

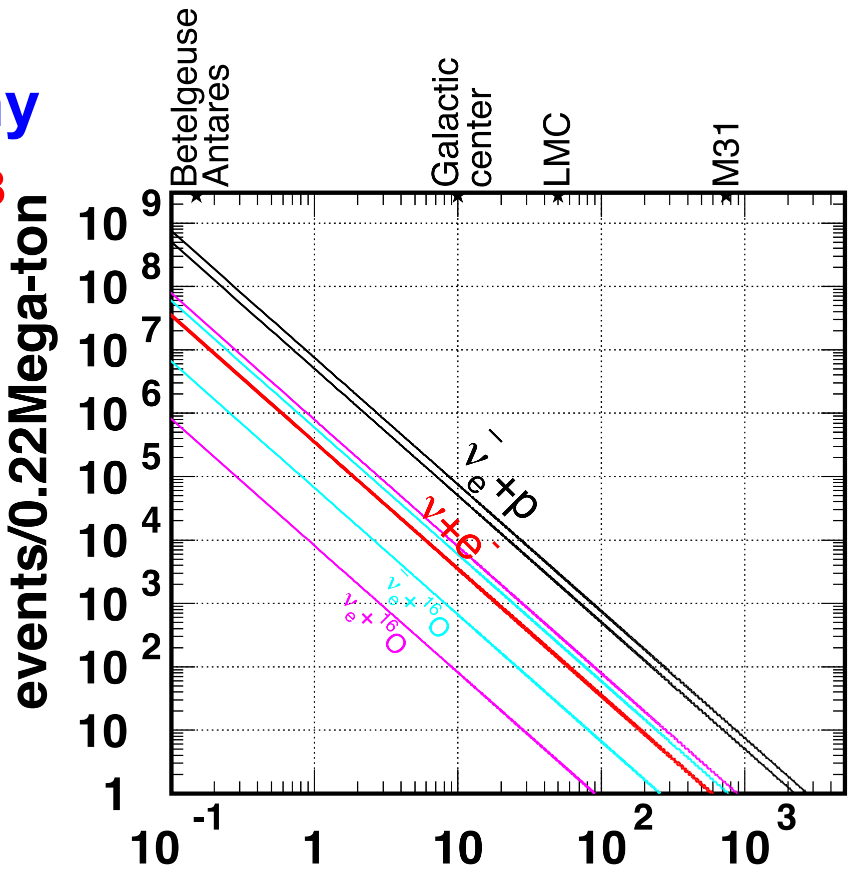
- Hyper-Kamiokande is sensitive to neutrinos from pre-supernova, core-collapse supernova bursts and from integrated relic supernova neutrino background
- Pre-supernova: Si burning ~2 days before core collapse, e.g. for 20 $M_\odot$, enhanced if Hyper-K loaded with Gd

Multi-messenger astronomy

MNRAS,461, 3296 (2016) arXiv:1602.03028

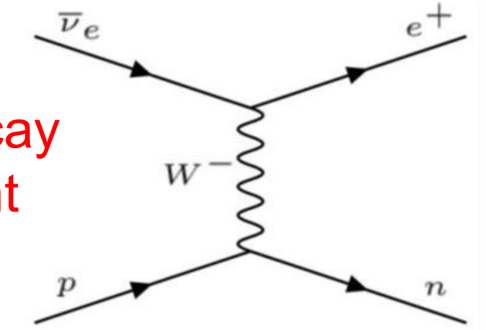


Time sequence 17 $M_\odot$ supernova



arXiv:1805.04163

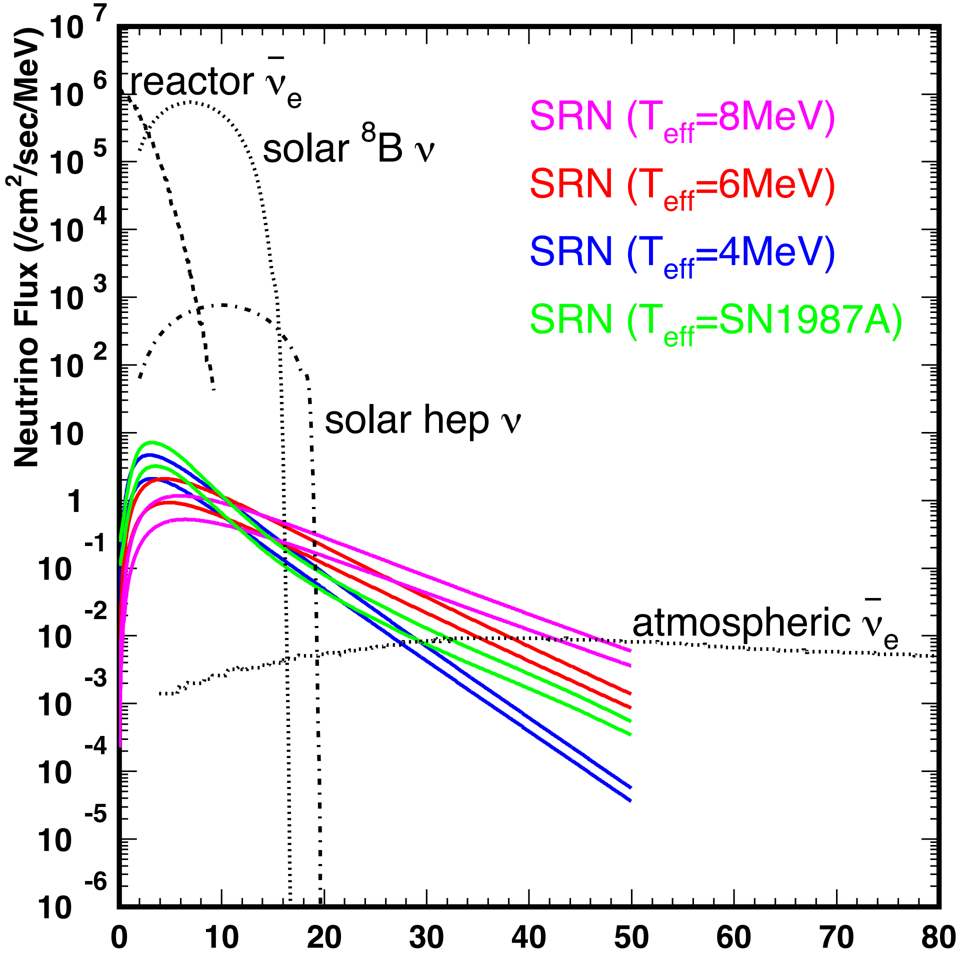
Inverse beta decay dominant channel



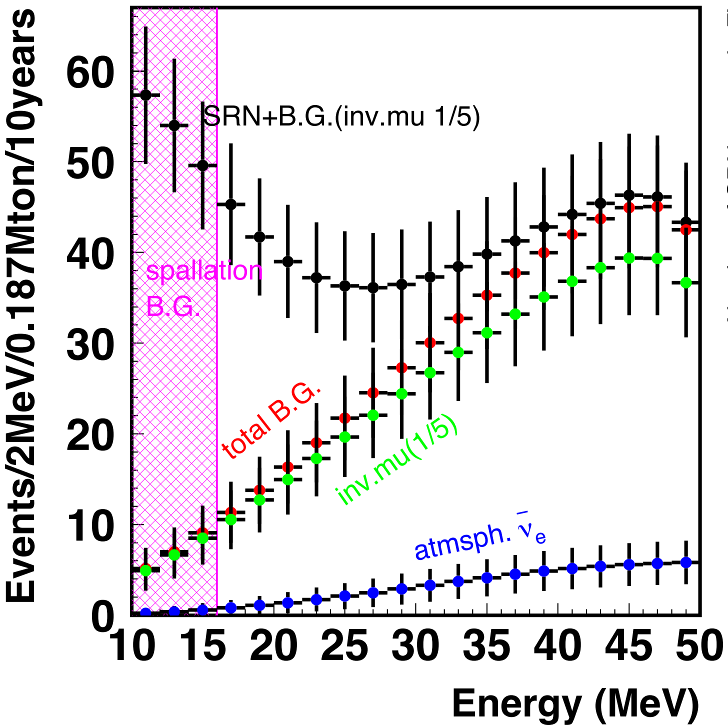
- Betelgeuse: ~10^8 events
- Expect ~50k-90k events at 10 kpc (galactic centre)
- Large Magellanic Cloud at 50 kpc: 3000 events
- Andromeda (M31) at 780 kpc: ~10 events

Supernova Relic Neutrinos (SRN)

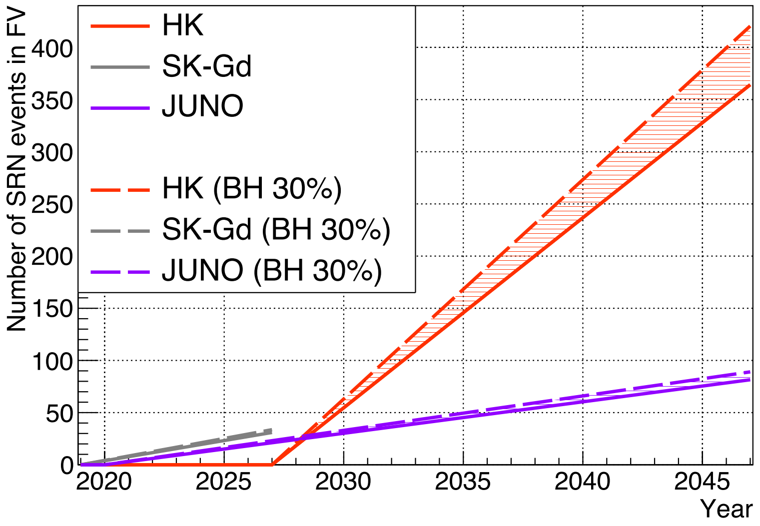
- Hyper-Kamiokande has sensitivity to integrated relic neutrino background: diffuse neutrinos coming from all past supernovae (window between 16-30 MeV)



16-30 MeV



Hyper-K 10-year detection with neutron tagging (67% efficiency)



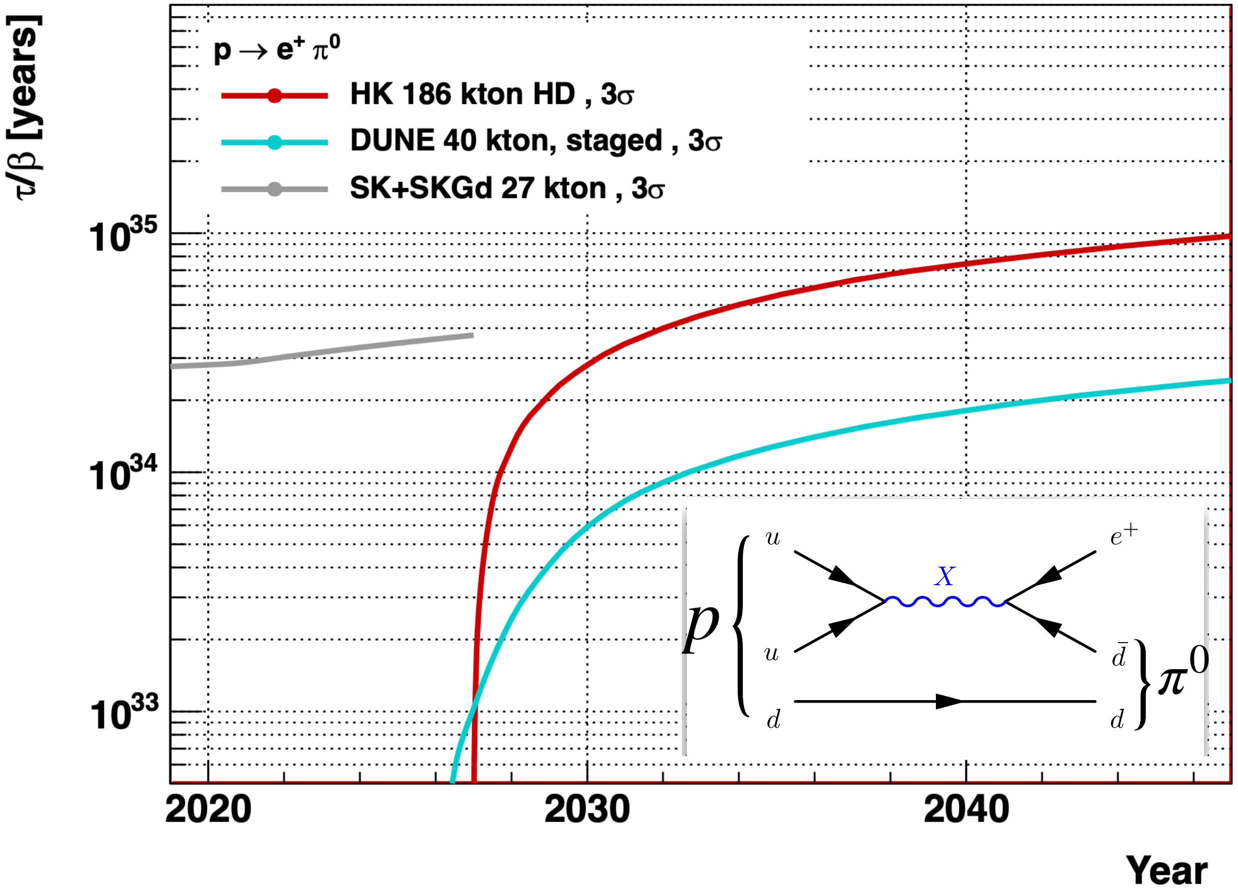
Number of supernova relic neutrinos in 16-30 MeV window (6 MeV ν temperature), without and with 30% ν at 8 MeV temperature from black-hole remnant

Proton decay

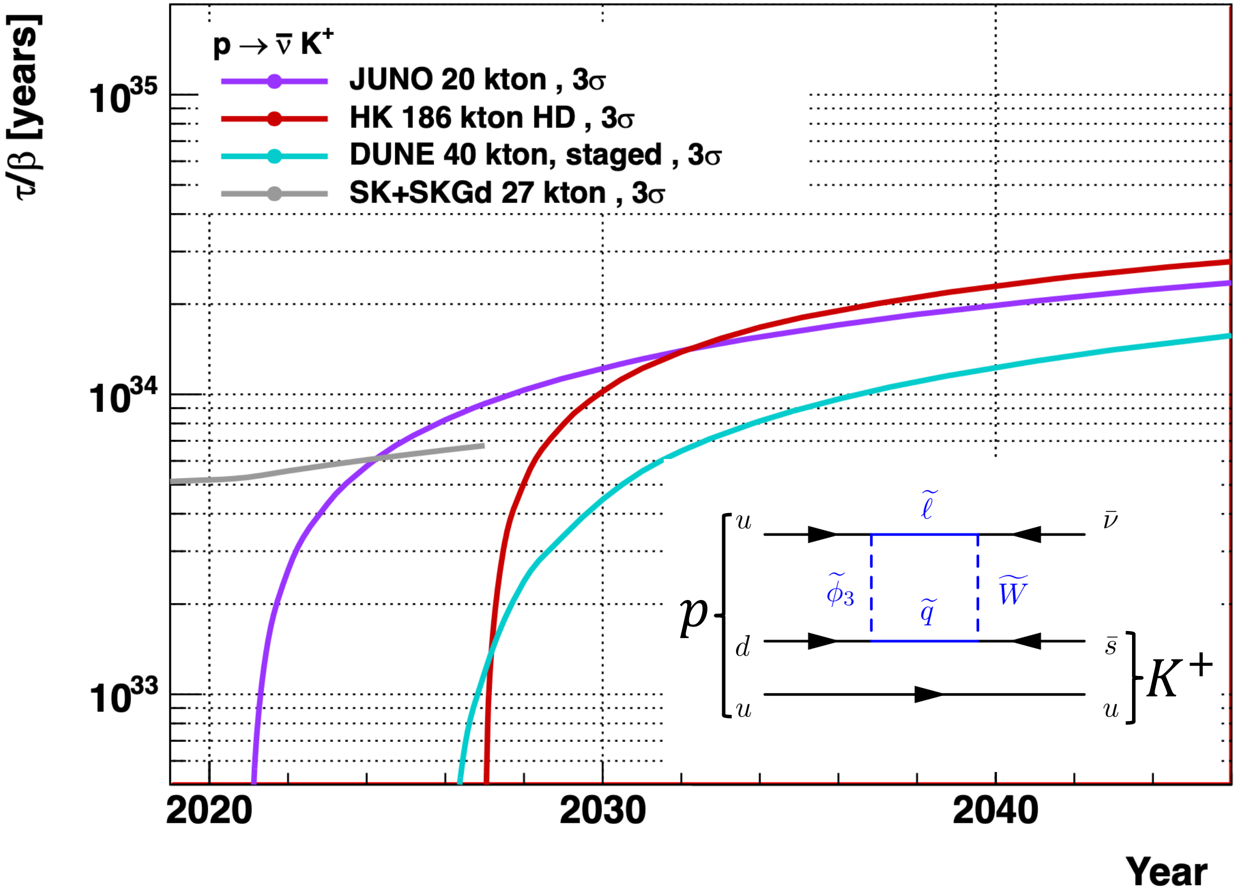
Hyper-Kamiokande

- Proton decay is evidence of Beyond Standard Model (BSM) and Grand Unified Theories (GUT)
- Examples of proton decay sensitivity in two modes:

$p \rightarrow e^+\pi^0$



$p \rightarrow \bar{\nu}K^+$

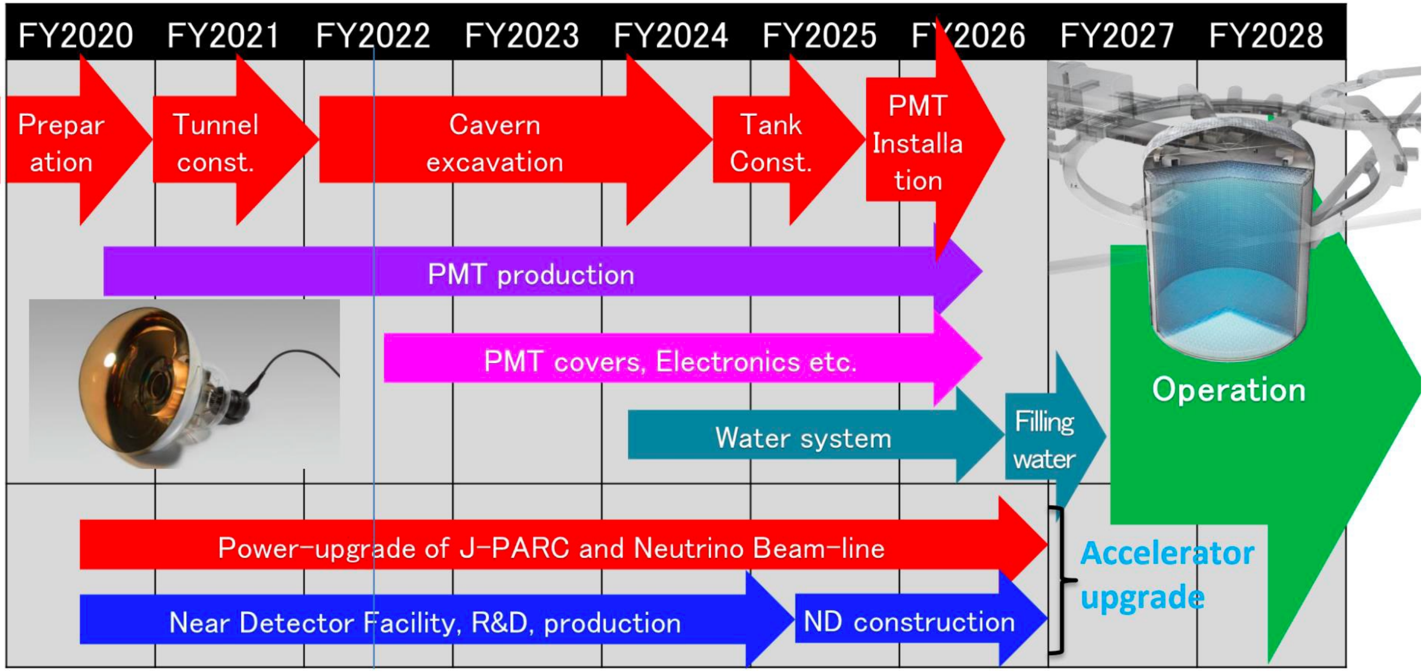


Only realistic chance of achieving $\tau(p \rightarrow e^+\pi^0) > 10^{35}$ years

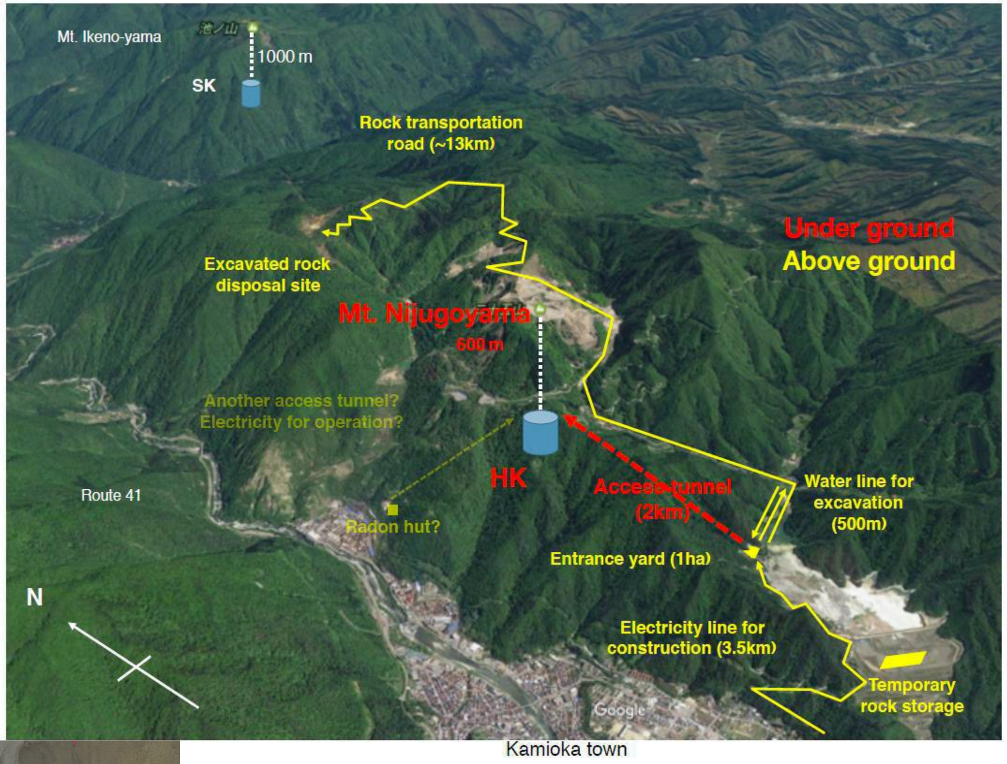
Hyper-Kamiokande Schedule and Civil Engineering

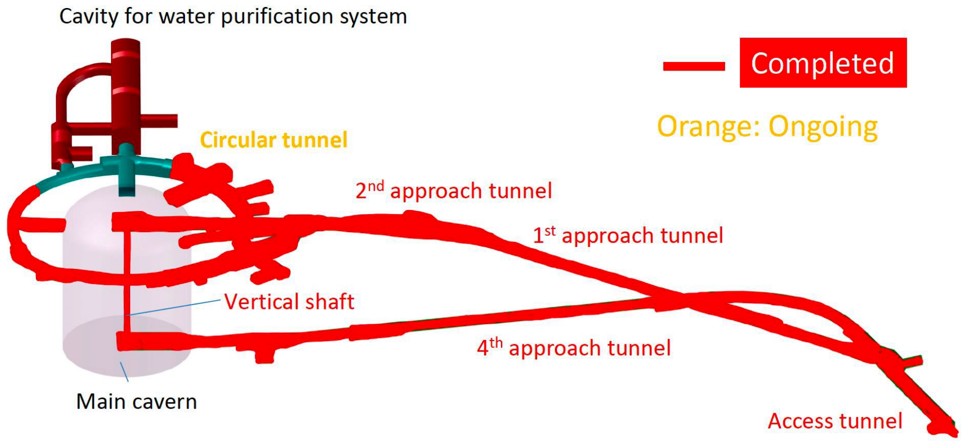
Hyper-Kamiokande

- Scheduled start of data-taking: 2027



Overview of Hyper-K construction





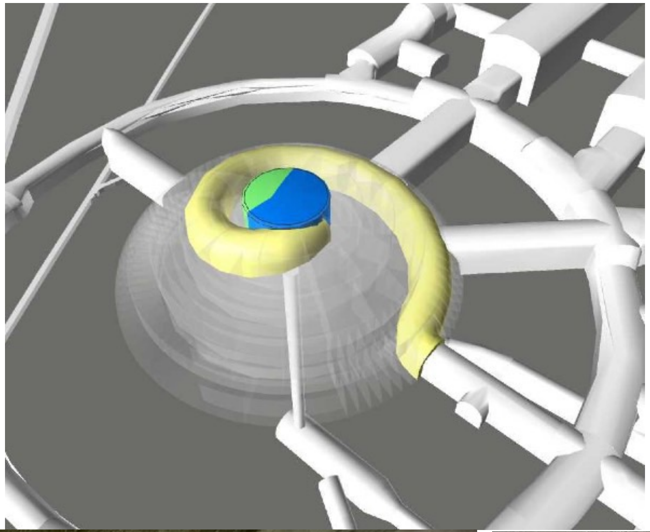
Access tunnels completed
Commenced cavern excavation
Civil engineering on track
Centre of dome reached June 2022

Hyper-Kamiokande Schedule and Civil Engineering

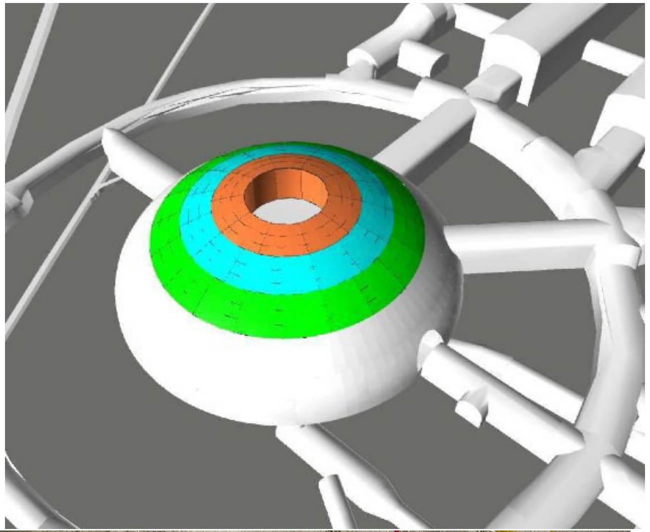
Hyper-Kamiokande

- Cavern excavation

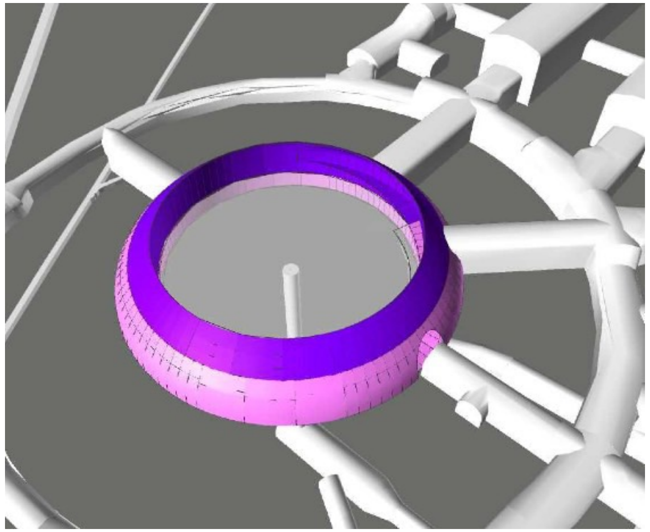
First ring

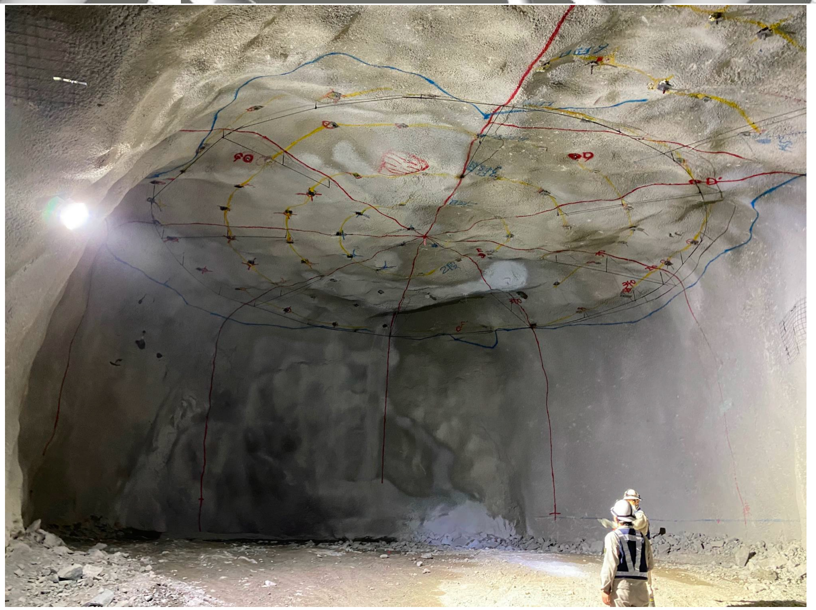


2^{nd} - 4^{th} rings



5^{th} - 6^{th} rings





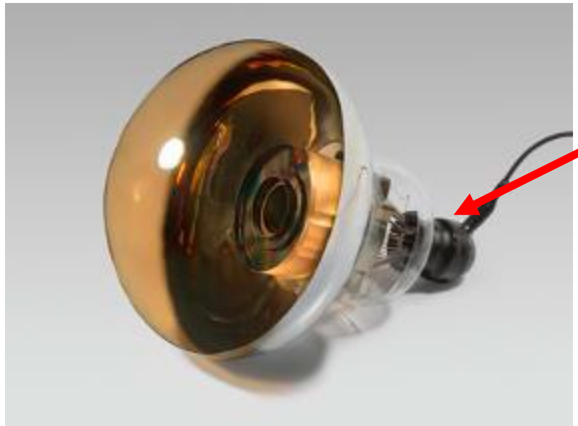
Cavern dome constructed in consecutive rings.

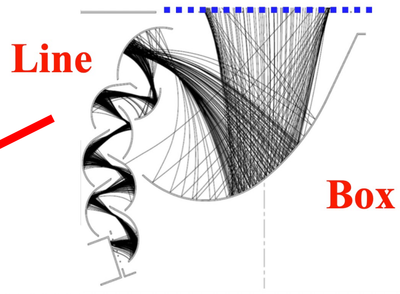
1^{st} – 4^{th} rings complete and working on 5^{th} ring

Excavation of dome on track

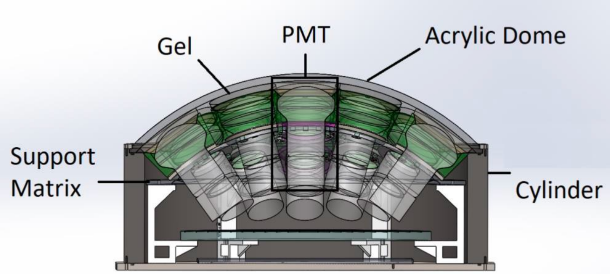
Hyper-Kamiokande Photomultiplier Tubes

- 20,000 Hamamatsu 20-inch box-and-line PMTs
- PMT production and quality assurance started





- ~2,000 multi-PMT modules (19 3-inch PMTs) for better vertex resolution performance



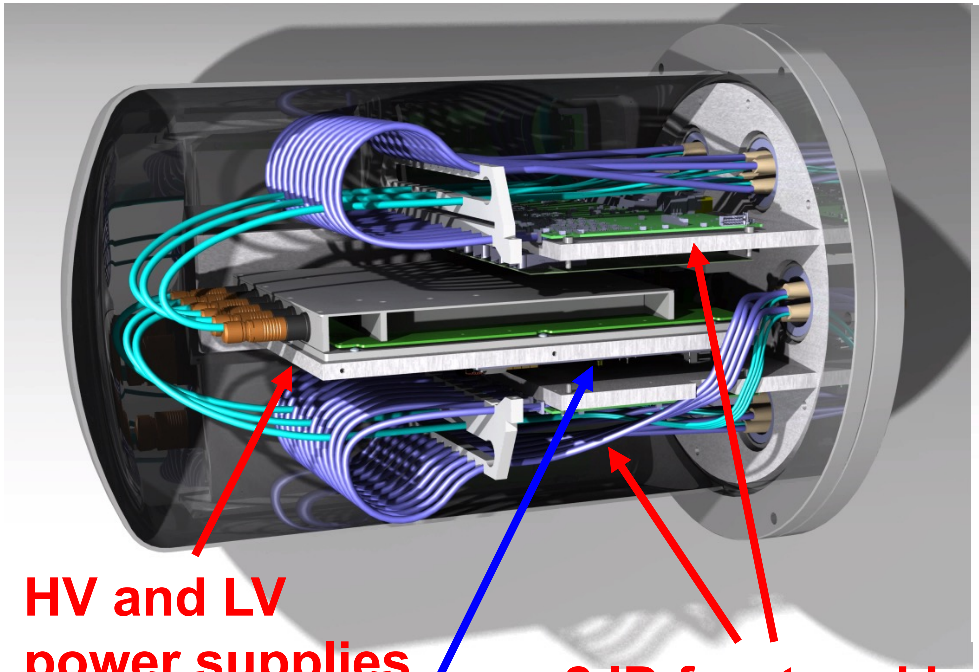
- ~7,200 Outer Detector 3-inch PMTs with wavelength shifting panels to veto cosmics

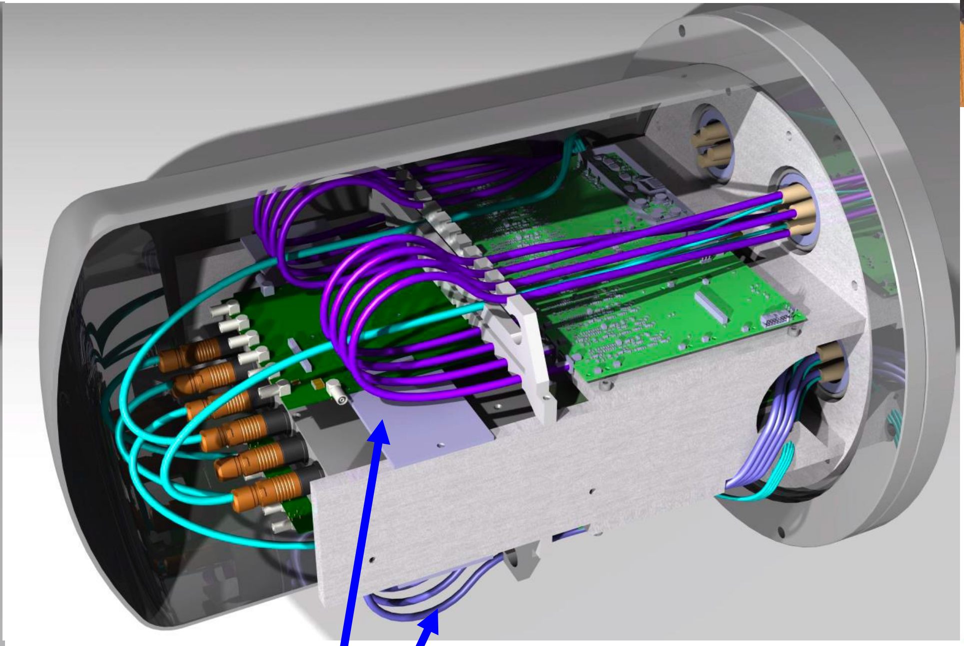
Ongoing studies to reduce number, by using Inner Detector reconstruction

Hyper-Kamiokande Electronics

- Front-end electronics placed in underwater vessels
- Two types of underwater electronics vessels
  - Inner detector vessels: 24 ID channels read out by two PCBs
  - Hybrid outer + inner detector vessels: 20 ID + 12 OD channels

Preliminary



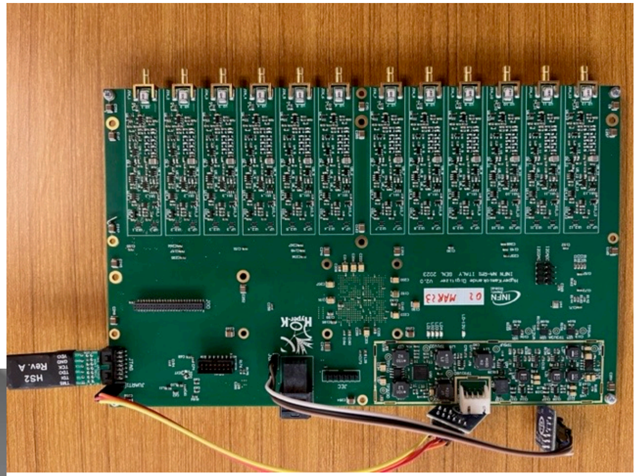


HV and LV power supplies

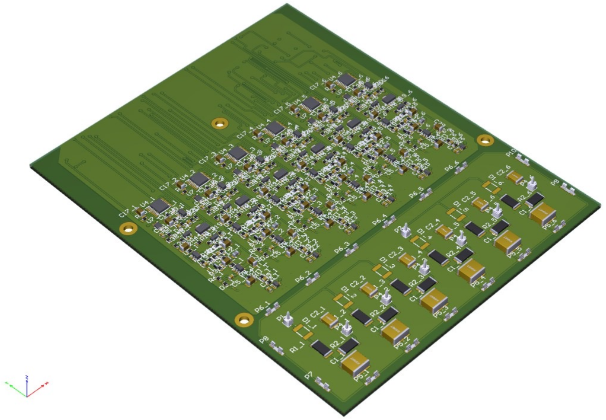
2 ID front-end boards

Data processing and timing boards

2 OD front-end boards



ID 12-channel front-end board



OD 6-channel FE board

Conclusions

Hyper-Kamiokande

- Hyper-Kamiokande is next generation water Cherenkov detector
- Hyper-K will produce world-leading results in:
  - Neutrino oscillations: search for CP violation (5σ sensitivity in 60% δ_{CP}) and determination of mass ordering
  - Solar and atmospheric neutrinos
  - Searches for supernova bursts and supernova relic neutrinos
  - World-leading proton decay search with expected lifetime sensitivity $> 10^{35}$ years
- Hyper-Kamiokande construction on schedule
  - World's largest underground facility: 260 kton water Cherenkov detector
  - Access tunnel and cavern construction on track
  - Photomultiplier production underway
  - Electronics and underwater electronics vessel designs being finalised
  - Neutrino beam upgrade to 1.3 MW
  - Near detector upgrade and design of intermediate detector being finalised

Hyper-Kamiokande

BACKUP

Neutrino oscillations

Hyper-Kamiokande

- Three-flavour oscillation formula for Hyper-K analysis:

$$P_{\nu_\mu \nu_e (\bar{\nu}_\mu \bar{\nu}_e)}$$
$$= \sin^2\theta_{23} \frac{\sin^2 2\theta_{13}}{(A-1)^2} \sin^2[(A-1)\Delta_{31}]$$
$$\mp \alpha \frac{J_0 \sin\delta_{CP}}{A(1-A)} \sin\Delta_{31} \sin(A\Delta_{31}) \sin[(1-A)\Delta_{31}]$$
$$+ \alpha \frac{J_0 \cos\delta_{CP}}{A(1-A)} \cos\Delta_{31} \sin(A\Delta_{31}) \sin[(1-A)\Delta_{31}]$$
$$+ \alpha^2 \cos^2\theta_{23} \frac{\sin^2 2\theta_{12}}{A^2} \sin^2(A\Delta_{31})$$

Matter enhances neutrino oscillations due to neutrino interactions

assuming:

$$\alpha = \Delta m^2_{21} / \Delta m^2_{31} \qquad A = (-)2\sqrt{2} G_F n_e E / \Delta m^2_{31}$$

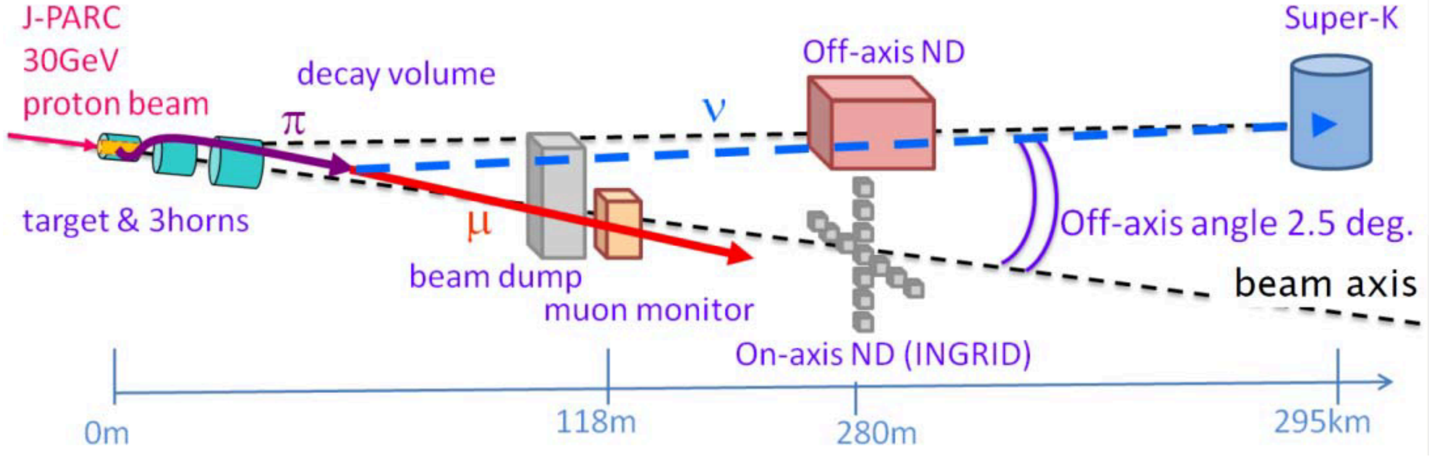
Parameter A depends on matter density n_e

$$\Delta_{ij} = \Delta m^2_{ij} L / 4E \qquad J_0 = \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\theta_{13}$$

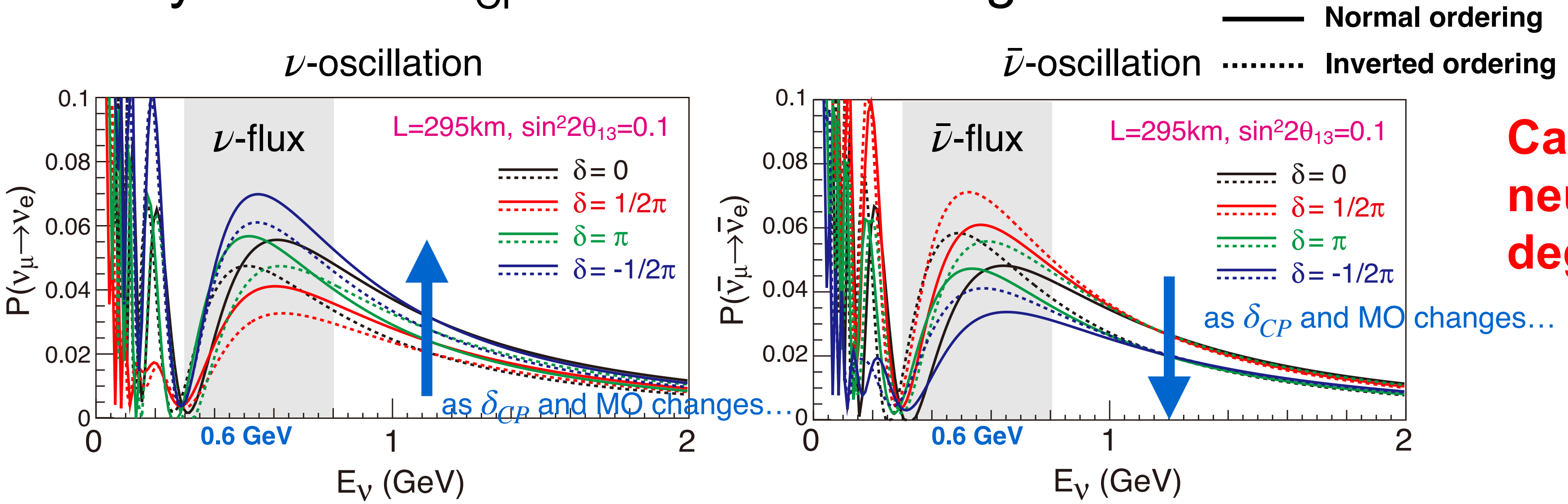
Neutrino oscillations in Hyper-K with neutrino beam

Hyper-Kamiokande

- Off-axis at 2.5° neutrino beam to achieve maximum neutrino flux at oscillation maximum of 0.6 GeV



- Degeneracy between δ_{CP} and mass ordering



Can use atmospheric neutrinos to break degeneracy

J-PARC beam, near detector and IWCD

Hyper-Kamiokande

- Neutrino beam at J-PARC being upgraded for T2K and for Hyper-K era, from 515 kW to 1.3 MW
  - Power supply upgrade: 250 kA → 320 kA;
  - Cycle: 2.48 s → 1.32 s → 1.16 s/cycle
- Upgrade of ND280: October 2023
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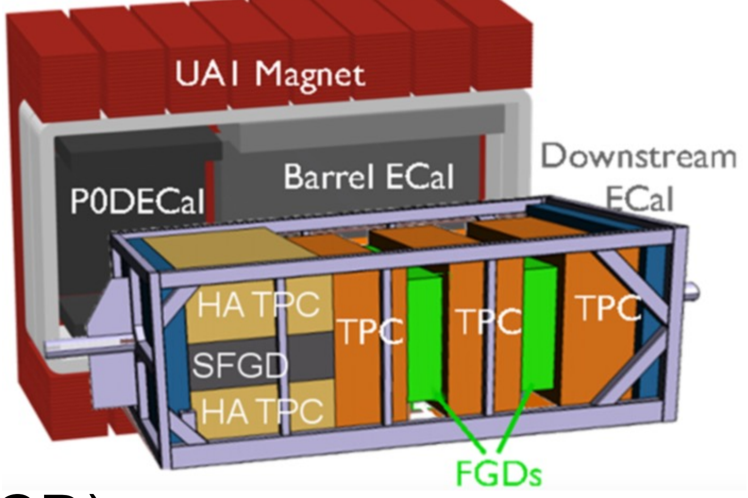

- New Intermediate Water Cherenkov Detector (IWCD):

Uses PRISM approach: change off-axis angle 1° – 4° to change mean neutrino energy and constrain:

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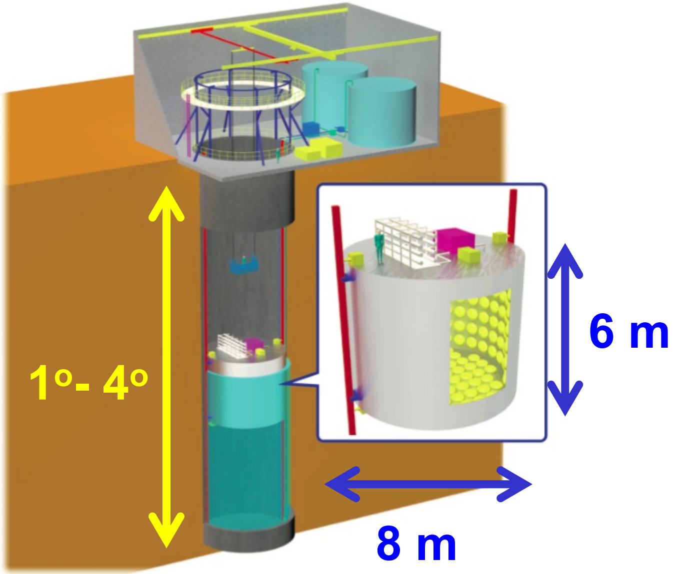
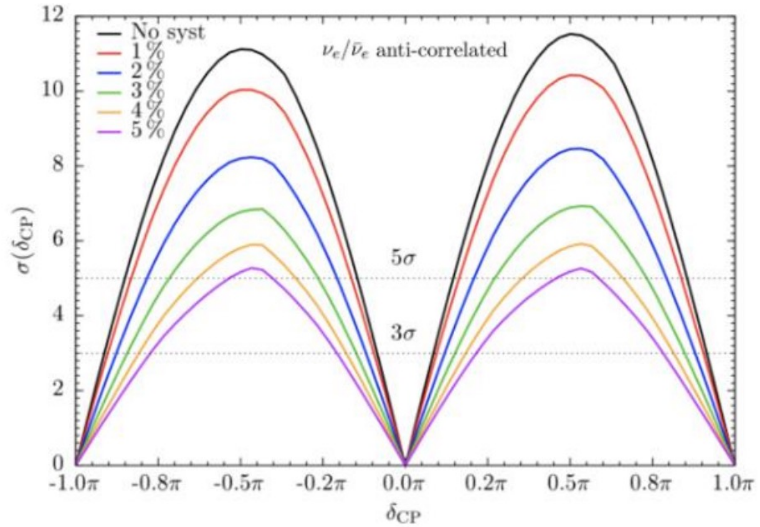
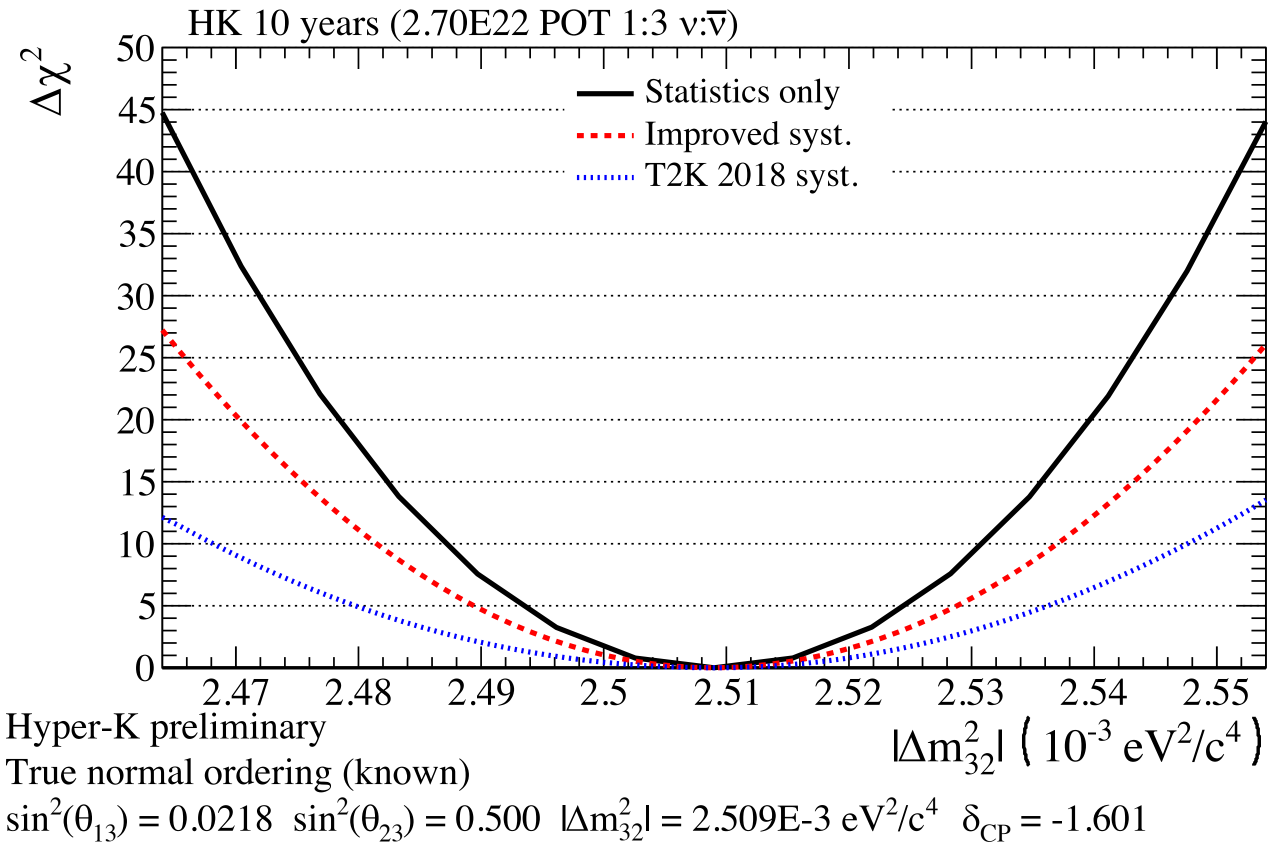
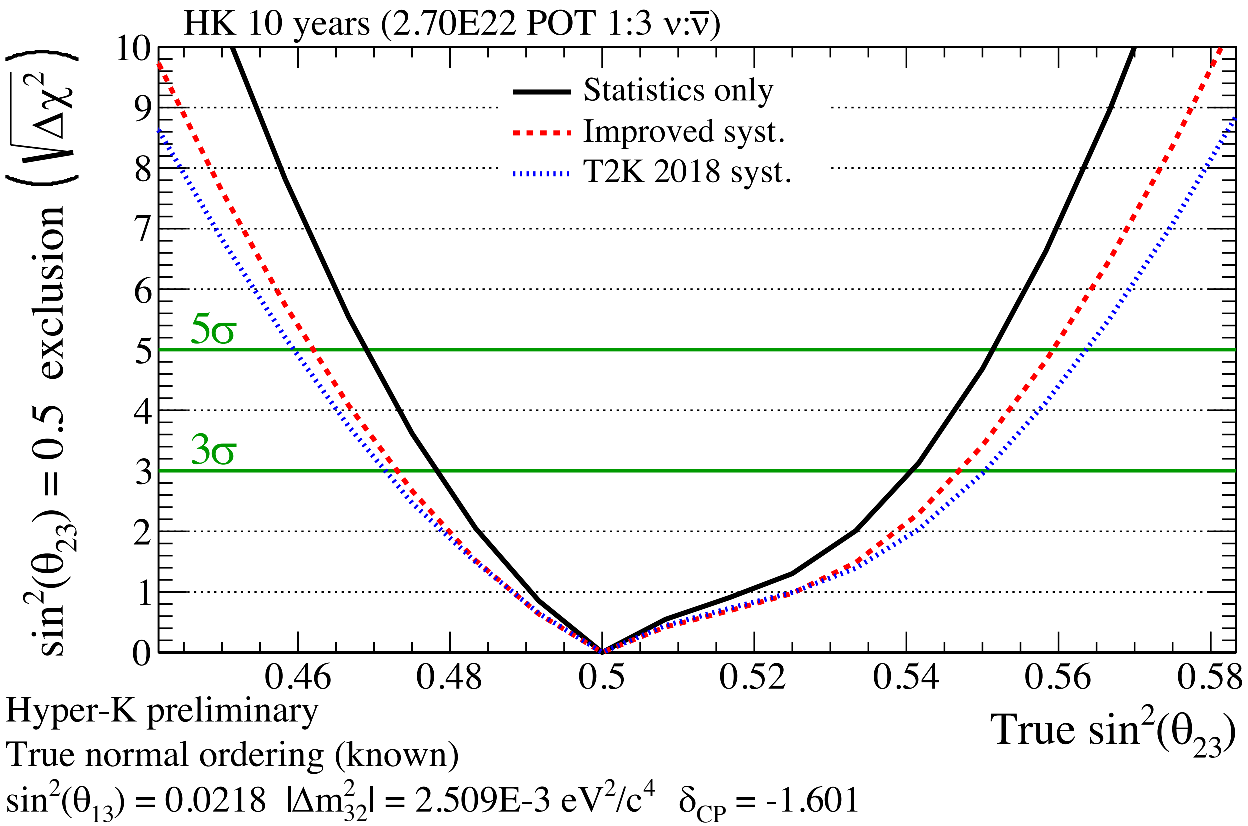




Neutrino oscillation sensitivity in Hyper-K

- Accuracy Δm^2_{32} and wrong octant $\sin^2(\theta_{23})$ sensitivity with improved systematics
- After 10 HK-years, $\sin^2\theta_{23}=0.5$ can be excluded at 3 sigma for true $\sin^2\theta_{23} < 0.47$ and true $\sin^2\theta_{23} > 0.55$

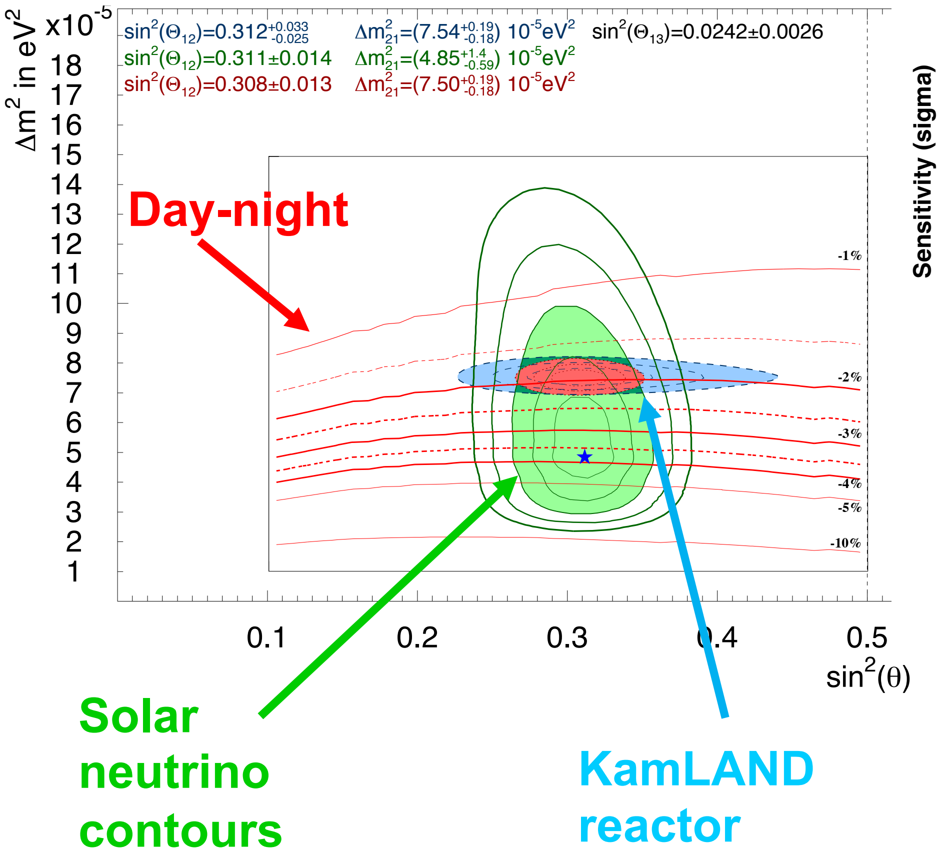


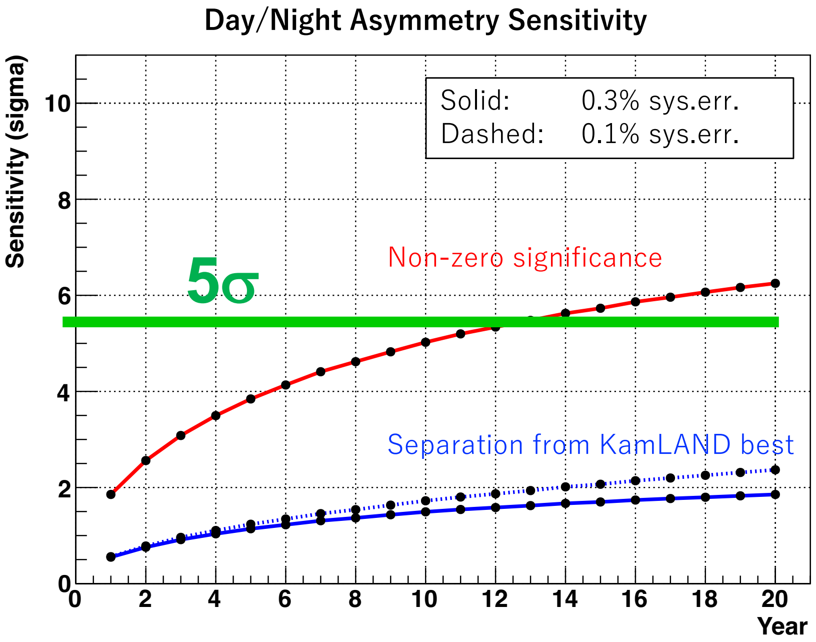


Solar neutrinos

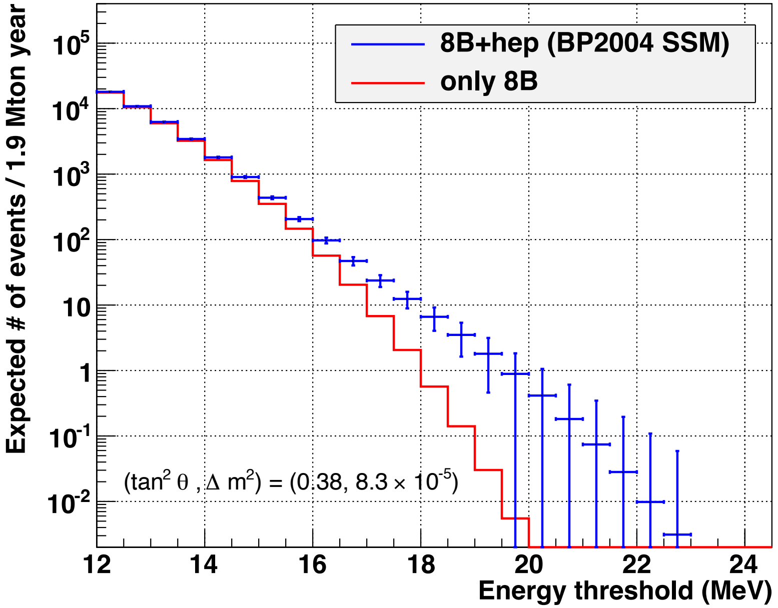
Hyper-Kamiokande

- Solar neutrino mixing parameters vs day-night asymmetry
- Day-night asymmetry: regeneration in matter on Earth (evidence MSW)
- Observation of HEP neutrinos above ^{8}B neutrinos





Day-night asymmetry with:
$\Delta m^2_{21} = 7.54\times10^{-5}\ \mathrm{eV}^2$**(reactor)**



HEP neutrinos: only solar neutrino process that remains to be discovered

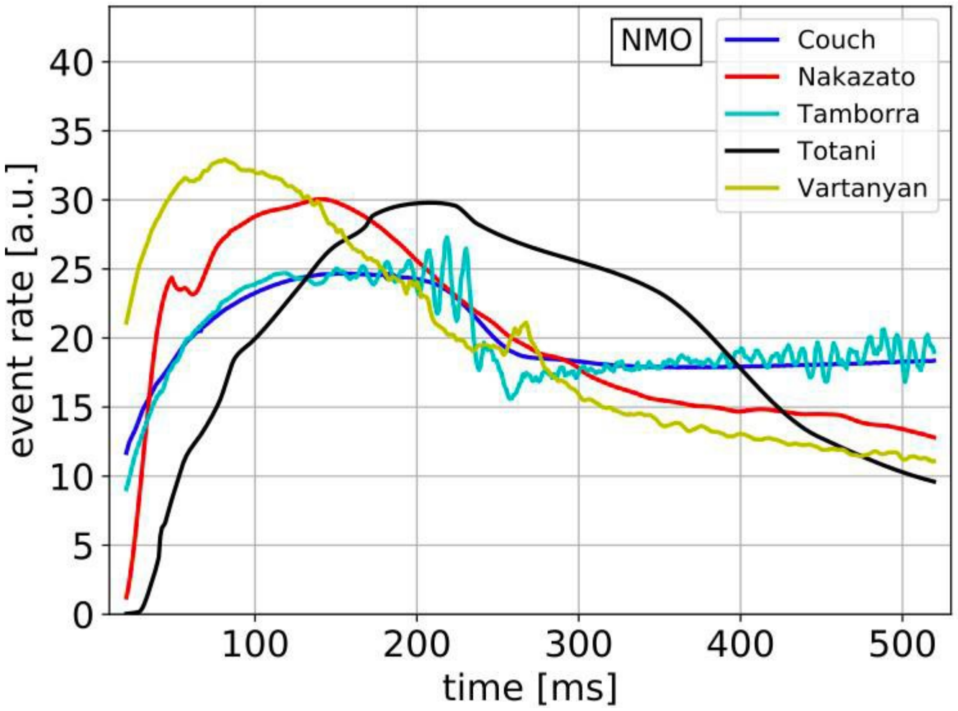
Supernova neutrinos in Hyper-Kamiokande

- Supernova model discrimination with Hyper-Kamiokande: five supernova models were considered

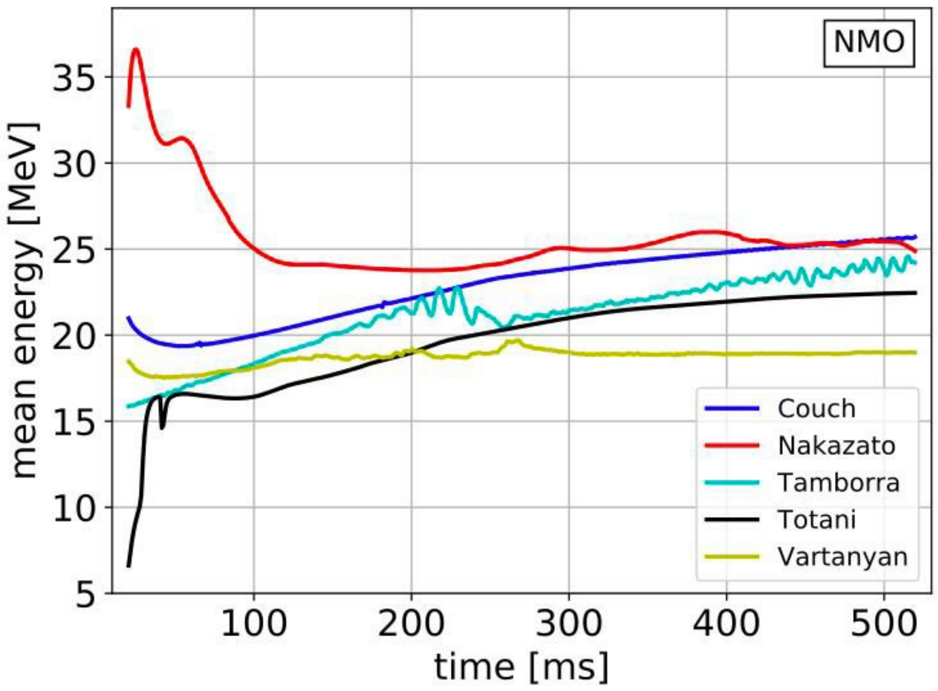
K. Abe et al., Ap. J. 916 15 (2021)

Model	Mass		events at 10 kpc*	N=100	N=300
Totani arXiv:astro-ph/9710203	20 $M_\odot$	1D	19716	140 kpc	81 kpc
Nakazato arXiv:1210.6841	20 $M_\odot$	1D	17978	134 kpc	77 kpc
Couch arXiv:1902.01340	20 $M_\odot$	1D	27539	166 kpc	96 kpc
Vartanyan similar to arXiv:1804.00689	9 $M_\odot$	2D	10372	102 kpc	59 kpc
Tamborra arXiv:1406.0006	27 $M_\odot$	3D	25021	158 kpc	91 kpc

Event rate vs Time



Mean energy vs Time

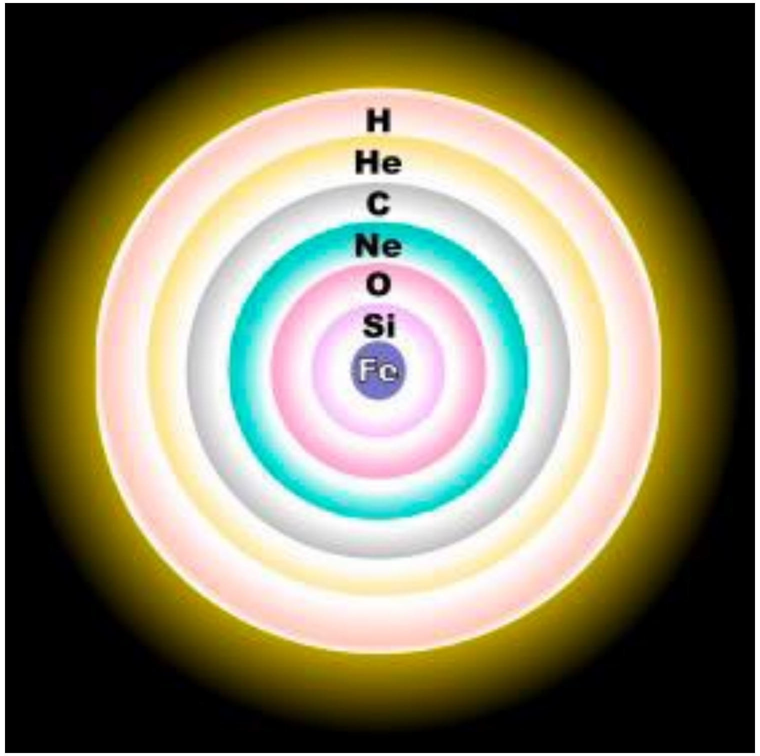


Pre-supernova neutrinos

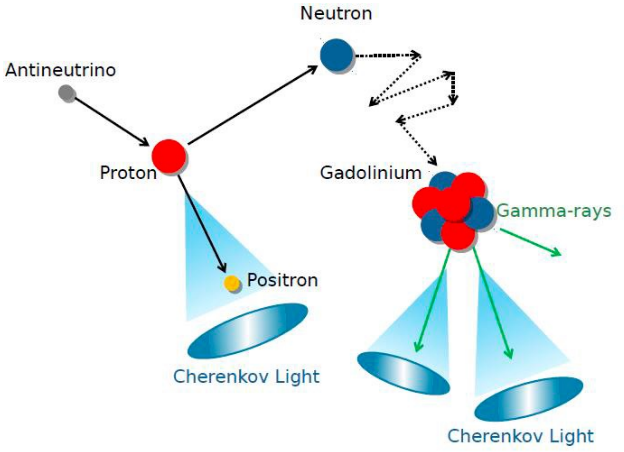
Hyper-Kamiokande

- Pre-supernova anti-neutrinos are from final stages of stellar burning
- Last stage before core collapse is Si burning

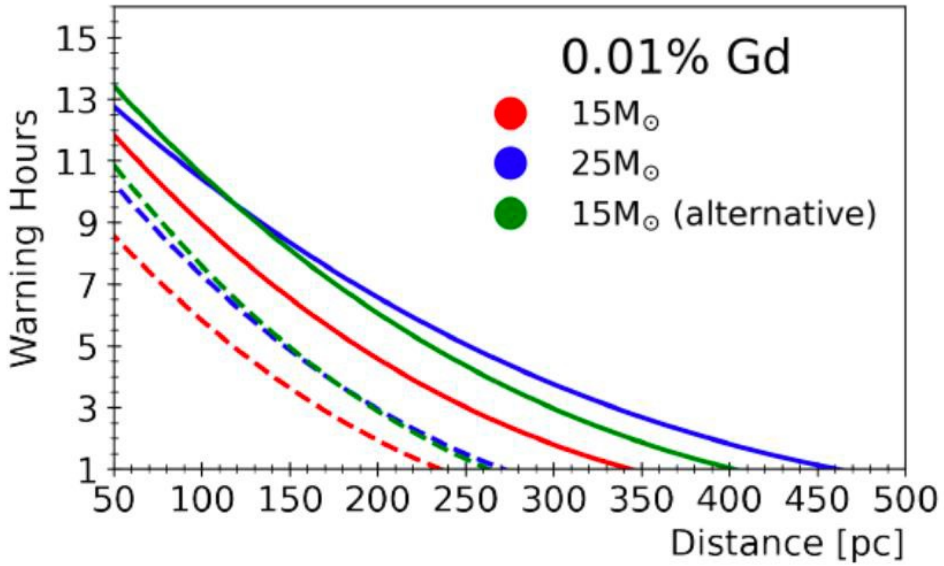
Burning Stage	Duration	ν_e ($\bar{\nu}_e$) fraction	Average ν energy
C	300 years	42.5%	0.71 MeV
Ne	140 days	39.8%	0.99 MeV
O	180 days	38.9%	1.13 MeV
Si	2 days	36.3%	1.85 MeV



Super-K has loaded Gd in water to detect neutrons more efficiently



Pre-Supernova alarm in Super-K with 0.01% Gd in water for early warning



L. Machado et al., Ap. J. 936 40 (2022)

- Could consider loading Gd also in Hyper-K to enhance pre-SN signal

Hyper-Kamiokande Detector Layout

- Layout detectors on inner frame: interleaving of components